LLG User Manual v2.50

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Published by
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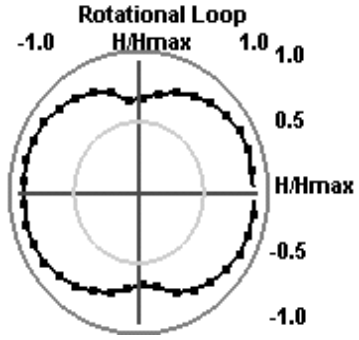
CHAPTER 1

LICENSE AGREEMENT AND RELEASE NOTES



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RELEASE NOTES

Below is a history of LLG version 2 releases and the new features of each release.

Version 2.0, Released November 1, 2000 with an Updated Manual

V2.0 was a major upgrade that included an entirely redesigned graphical user interface, faster calculating time and the following dozens of new features:

1. Document interface
   - Run multiple problems simultaneously.
   - Run a simulation and a movie simultaneously.
2. Graphics
   - Multiple OGL windows and views
   - Multiple simultaneous perspective views
   - Input cells
   - Variable contours
   - Contour indicator
   - Material color codes
   - Variable color maps
   - Variable color wheels
   - Variable 3D glyphs
3. Graphics representation
   - Current flow
   - Position dependent external fields
4. Integrated electron phase
5. Utilities
   - Disk information
   - Clock
   - Calculator
   - Graphical picker
   - Enhanced persistent graphical picker
6. Input configuration
   - Arbitrary number of material layers
7. Input parameters
   - Fourth-order uniaxial anisotropy
8. Boundary conditions
   - Continuous 2D is no longer a feature.
9. Currents
   - AC Currents (superimposed or not)
   - Time dependent currents
   - Time dependent current editor
10. Layers
    - An unlimited number of material layers
11. GUI input for layer boundary conditions
12. Time dependent h field
    - AC fields
    - Fixed time fields
    - Arbitrary waveforms and waveform editor
13. 3D finite permeability shields
    - Imaging BC magnets
    - Response to media
    - Cross track response
    - Moving media
14. Position dependent parameter editor
    - Variable 3D resistivities
    - Extended media model input editor
    - Variable surface tiling/coupling editor
    - Parameter histogram viewer
    - BC parameter viewer

Version 2.05, Released April 2001, with an Updated Manual

With v2.05 you can:

1. Examine convergence, hysteresis or hysteresis-part files in a 2D graphics environment.
2. Simulate a movie.
3. Extract hysteresis data from a movie file.
4. Edit movie files.

Version 2.05b, Released Electronically March 18, 2001

V2.05b features are:

1. 2D graphics:
   - Print the page.
   - Copy graph to clipboard.
   - Save graph to a bitmap file.
2. MFM imaging was changed for speed:
   - To compute an MFM image, enter Z height and mode, then check the Compute MFM box. The MFM mode will not be recomputed until this box is checked again; each click results in one computation.
   - Since the same array holds all computed views, if you have other computed views checked, the MFM field data will be valid on the screen but not for file saving.

- To save the MFM data to a file ***ACCURATELY***, be sure that ***NO*** other computed views (torques...) are selected; the one and only computed view is the MFM view selected.

Version 2.1, Released April 2001, with an Updated Manual

With v2.1, you can:

1. Warp bitmap and contour graph types in 3D.
2. Overlay color, arrows and contours onto the selected graph type.
3. Specify minimum and maximum Iterations.
4. Specify either the absolute value of the:
   - largest normalized torque
   - average normalized torque
   - largest change in single direction cosine
   - average of all direction cosines

Version 2.2, Released June 2001, with an Updated Manual

With v2.2, you can:

1. Specify demagnetization edge correction.
2. Specify adaptive integration.
3. Implement Gause-Seidel integration.
4. Import bitmap files for position dependent parameters.
5. Define edge magnetization and edge roughness effects.
6. Specify 3D Voronoi cell discretization.
7. Interpolate movies.
8. Edit the numerical values of graphics.
9. Save and load graphics to LLG.

Version 2.3, Released July 2001, with an Updated Manual

1. Run problems in batch mode.
2. View and organize LLG files with a journal viewing tool.

Version 2.45, Released August 2002, with an Updated Manual

1. Atomic lattice computations.
2. Asymptotic energy fitting in 2D Graphics environment.
3. Remove k=0 component of residual flux in periodic problems using the 3D complex FFT solver.

Version 2.46, Released August 2002, with an Updated Manual

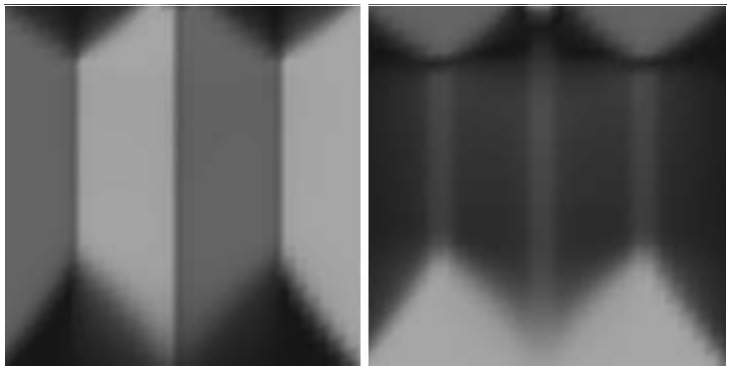
1. Spin torque computations.
2. Interface anisotropy for layers.
3. Dynamic magnetization visualization.

Version 2.47, Released December 2002

1. FMR/Dynamic suseptibility.
2. Demag. field calculator utility.

Version 2.50, Released June 2003, with an Updated Manual

1. Updated domain viewer utility.
2. Time and position dependent external fields.
3. Heff field flagging.



SYSTEM REQUIREMENTS

- To install and run LLG Micromagnetics Simulator you must have at least the following:
- A 600 MHz Pentium Pro III.
- 256 MB of RAM.
- A video card that supports a minimum of 16 million colors at 1280 x 1024 resolution, such as the ELSA Winner 2000 ProX (4-MB RAM) or the Matrox Millennium II (4-MB RAM).
- A 17” monitor that supports at least 1280 x 1024 at 70 Hz, although the letters appear rather small.
- At least Service pack 3 for NT4.0 workstation (Win2000/Win xP are acceptable).

To take advantage of LLG on an NT 4.0 Workstation, you should have the following:

- A Pentium III 733 MHz CPU. Dual CPUs are supported by LLG.
- 512MB of RAM are required for larger problems. A computer with a 512MB capacity allows you to add memory as needed.
- An Adaptec 2940 UltraWide SCSI adapter (68-pin adapter), 18 GB hard drive for data and a 4 mm DAT tape backup are recommended. Fast SCSI controllers are good for accessing disk files quickly.
- A high-end fast OpenGL video card, such as 3D LABS Oxygen video card, (32 MB RAM and a Glint chip).
- A 21” monitor, such as the View Sonic 810, which supports resolutions up to 1600x1200 at 70Hz.

MEMORY REQUIREMENTS OF LLG CALCULATIONS

LLG will have the following approximate memory requirements. The numbers in the table below are based on a Permalloy structure with 10 nm cubic cells.

Approximate Structure Size	*Pixilation*	*# Pixels*	*Layers*	*Position Dependent*
500 nm x 500 nm x 50 nm	50 x 50 x 5	12500	23 MB	27 MB
1000 nm x 1000 nm x 50 nm	100 x 100 x 5	50000	82 MB	95 MB
2000 nm x 2000 nm x 50 nm	200 x 200 x 5	20000	315 MB	369 MB
4000 nm x 40000 nm x 50 nm	400 x 400 x 5	80000	1245 MB	1461 MB

INSTALLING LLG MICROMAGNETICS SIMULATOR

- Log onto your system as the Administrator.
- Use the control panel to open the display control. Set your display settings to 1280 x 1024 @ 16.7 million colors. Set the fonts to small fonts.
- Insert the CD-ROM.
- From Explorer, open the CD-ROM and double-click on Setup.exe. This activates InstallShield, which automatically sets up LLG.
- You will be prompted to enter a Serial Number. Since the installation is not protected, you may enter anything you like into this field, but you must enter something.
- You will be prompted for an install directory. Use the NT interface to select a new directory or use the default. The files will automatically be installed into this directory.

INSTALLING THE PROTECTION KEY

The Protection Key must be installed directly onto the parallel printer port on your computer's backplane. If you have a parallel printer that is connected to this port, simply install the Protection Key between the parallel port and the printer cable. Printer functionality will not be impaired.

INSTALLING THE PROTECTION KEY DRIVER

1. The program for installing the Protection Key Driver can be found in the LLG Micromagnetics program installation directory. Double click on the folder named Rainbow. Then, double click on Setupx386.exe. You must be logged on as the System Administrator to install the driver.
2. A set-up window with a function menu at the upper left will appear. Click on the functions menu and select Install Sentinel Driver.
3. You will be prompted for the path to the drivers, which should be correctly determined. The drivers are located in the i386 subdirectory in the Rainbow folder. Choose OK.
4. Then, reboot your system.

5. Test the Protection Key by double clicking on keyscan.exe in the llg directory. Click on the test button and observe the current date, last run date and expiration date of the program. As shown below, you should see Success written in all four edit fields at the lower left. A Version 2 key will display a 2 in the Key Version edit field. If your key displays a 2, you can run both v1 and v2 of LLG. If your Protection Key fails, contact LLG Micromagnetics immediately.

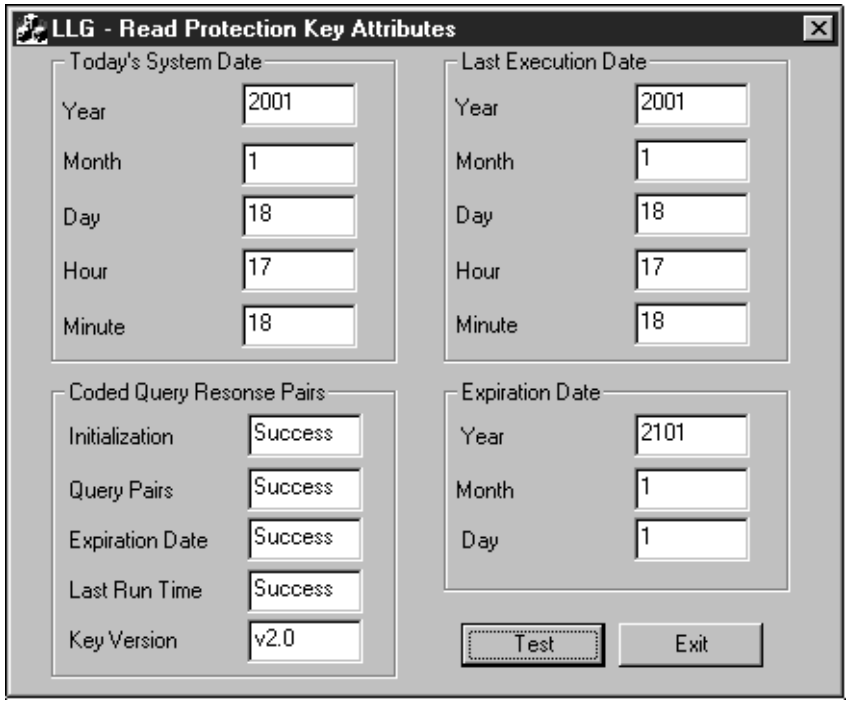


FIGURE 1. Keyscan Menu for Probing Protection Key Attributes

INSTALLING LLG WITH WINDOWS 2000 OR WIN XP

For installing LLG on a computer with Windows 2000 or Win xP:

1. Make a new directory in your LLG directory called WIn2000Files and move the following.dll files into the Win2000Files directory:
   - Gdi32.ddll
   - Glu32.dll
   - OpenG132.dll
   - Kernel32.dll
   - User32.dll
   - Ole32.dll
   - Msvcp60.dll

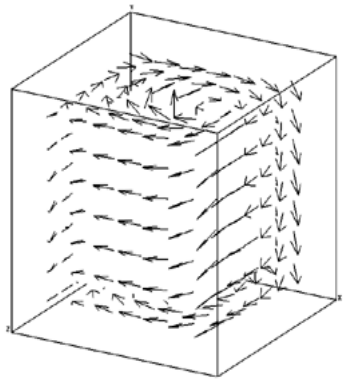
On Win2000/WinxP systems, you may experience graphics irregularities. This stems from Microsoft's graphical optimization algorithms which may circumvent the OpenGL drivers. If you experience problems, right click on the display desktop-window and select properties. Choose settings and click on the advanced button. Now choose the Troubleshooting page. Turn off hardware acceleration. Try LLG, which should now display the graphics. Now, iterate on the above process, gradually increasing the acceleration to an optimized setting where LLG graphics are still displayed.

INSTALLING LLG IN KANJI AND HANGUL ENVIRONMENTS

To install LLG in kanji and hangul environments, you might need to move a copy of msvcrt.dll from the LLG directory into your system32 folder. Please send any questions to llgmicro@mindspring.com.

CHAPTER 3

INTRODUCTION TO USING LLG



This section provides you with an overview of LLG's design, of how to use LLG and of LLG's functionality. For complete details and instructions, refer to the appropriate sections found later in the Manual.

THREE MODULES OF FUNCTIONALITY

LLG Micromagnetics Simulator has three functional modules. These modules are specified in terms of the serial process of defining the solutions to most problems, while maintaining consistency with the Windows event-driven programming interface. These modules are listed below with their corresponding menus.

- Input phase: data specification (LLG Input Sheet)
- Simulation phase: solution of the differential equations (LLG Simulation Sheet)
- Review phase: playback of results through graphical animation (movies) (LLG Movie Viewer)

INPUT PHASE: DATA SPECIFICATION

The **LLG Input Sheet** is the central interface for coordinating input parameters, error checking and setting critical global parameters. In general, inputting data specifications is the most tedious aspect of numerical simulations. The program has been designed to allow you flexibility in customizing simulations; however, this makes the data specification phase time-consuming and increases the risk of input error. Although, as a counter measure, LLG performs exhaustive error checking to prevent floating-point exceptions, defining a structure and how well it models an actual material or device is ultimately the user's responsibility.

Since the program solves the Landau-Lifshitz-Gilbert equations using finite differences for exchange energies and fields, as well as boundary elements for magnetostatic self-energies and fields, the structure of interest must be defined as a grid. The program uses rectangular pixels on a Cartesian grid. Although you can change the material parameters, including eliminating magnetic material altogether, this must be done on a Cartesian grid.

Once you have specified the structure and clicked the **Begin Simulation** button, LLG initializes all of the arrays, computes the demagnetization field coupling tensors and calculates the fields for any boundary conditions. Once these large arrays have been specified, the simulation phase can begin. Also, you are prompted to store the simulation parameters in several files.

SIMULATION PHASE: SOLUTION OF THE DIFFERENTIAL EQUATIONS

Once LLG has verified that you have input the data correctly, you have your first chance to set the graphical representation of the data. Many features can be viewed interactively.

REVIEW PHASE: PLAYBACK OF RESULTS THROUGH A GRAPHICALLY ANIMATED MOVIE

Once a simulation is complete, you can review the results by replaying them through a graphically animated movie or you can view a domain or field file in the viewer control. Graphical representation of the data is essential to comprehending the results of a simulation. The program provides complete two- and three-dimensional views in the form of bitmap images, contour maps and vector fields.

THEORY OF OPERATION

Micromagnetic structure, such as that present in surface domain walls, can be extracted with standard methods for the solution to the Landau-Lifshitz-Gilbert equation. Such methods have been given in the literature by Brown [1], LaBonte [1,2], Aharoni [3-9], Hubert [10,11], and Schabes [9,12]. The equilibrium magnetization configuration results from the minimization of the system's free energy. The energy of a ferromagnetic system is composed of 1) the mean field exchange energy E_{ex} between nearest neighbors characterized by the exchange coupling constant A (erg/cm); 2) the magnetocrystalline anisotropy energy E_K, which describes the interaction of the magnetic moments with the crystal field characterized by the constant K_v (erg/cm^3); 3) the surface magnetocrystalline anisotropy energy E_{ks}, which corrects for broken symmetry near surfaces in the interaction of the magnetic moments with the crystal field, and is characterized by the constant K_s (erg/cm^2); 4) the magnetostatic self-energy E_s, which arises from the interaction of the magnetic moments with the magnetic fields created by discontinuous magnetization distributions both in the bulk and at the surface; 5) the external magnetostatic field energy E_h, which arises from the interaction of the magnetic moments with any externally applied magnetic fields; and 6) the magnetostrictive energy E_r, which arises when mechanical stress (strains) are applied to a ferromagnetic material thereby introducing effective anisotropy into the system characterized by K_m (erg/cm^3).

The solution for the equilibrium magnetization distribution is a constrained boundary value problem in two or three spatial dimensions with the constraint of constant magnetization M_s. The continuous magnetization distribution of a ferromagnet is approximated by a discrete magnetization distribution consisting of equal volume cubes (3-D) or rods (2-D). Each individual discretized magnetization cell, interior to the array, will be addressed by the (X, Y, Z) coordinates of its centroid. There are N_x cells along X, N_y cells along Y, and N_z cells along Z interior to the structure to be modeled.

There is one plane (3-D) or column (2-D) of boundary cells bounding the discretized region. These boundary cells (conditions) can reflect the continuous uniform magnetization distribution present within the domains themselves on either side of the structure. If no boundary conditions are specified, the cells at the edges are free. In the absence of surface anisotropy, the normal derivative of the magnetization distribution at the surface is zero [2,13]. In the presence of surface anisotropy, the Rado-Weertman boundary conditions is used [13,14].

Fundamental to the solution of the micromagnetic equations is the assumption that the bulk saturation magnetization M_s (emu/cm^3) is constant microscopically throughout the ferromagnet. The parameter M_s represents saturation magnetization at room temperature. For most practical systems being considered (Fe, Co or Permalloy), there is little deviation in M_s at room temperature from the 0 K value. The value of the magnetization vector $\mathbf{M}(\mathbf{r})$ at each point within the ferromagnet is the saturation magnetization multiplied by the direction cosines, that is $\mathbf{M}(\mathbf{r}) = (M_x(\mathbf{r}), M_y(\mathbf{r}), M_z(\mathbf{r})) = M_s\alpha(\mathbf{r}) = M_s\,(\alpha(\mathbf{r}), \beta(\mathbf{r}), \gamma(\mathbf{r}))$. The constraint equation implied by the constant magnetization assumption is $|\alpha(\mathbf{r})| = 1$. The individual contributions to the energies in this continuum model are calculated by integrating the energy expressions over the structure in question. The energy integrals below are integrated over the appropriate dimension, dV. The exchange energy E_{ex} in the continuum approximation is given by.

$$E_{ex} = \int dV[|\nabla\alpha|^2 + |\nabla\beta|^2 + |\nabla\gamma|^2]$$

The exchange parameter A can be extracted from spin-wave theory [15-17], which shows that $A = A'M_s^2 = DS/2V$, where D is the spin-wave dispersion parameter, S is the spin per atom and V is the volume per atom. The spin-wave dispersion parameter, D, is related to the exchange constant, J, in the Heisenberg hamiltonian by D = 2JSa2, where 'a'

is the lattice spacing. This relationship is true for spin-wave modes along bcc [100], bcc [110], fcc [110] and fcc [100] directions.

The volume magnetocrystalline anisotropy for uniaxial (e.g. easy-axis in y) E_{Ku}, and cubic crystals E_{Kc}, is given by the following expressions, respectively,

$$E_{Ku} = \int dV\left[K_{u1}(1-\beta^2) + K_{u2}(1-\beta^2)^2\right]$$

$$E_{Kc} = \int dV\left[K_{c1}\left(\alpha^2\beta^2 + \beta^2\gamma^2 + \alpha^2\gamma^2\right) + K_{c2}\alpha^2\beta^2\gamma^2\right]$$

where the bulk anisotropy constants for cubic, Kc, and uniaxial, Ku, symmetry can be determined from torque magnetometry measurements. The energy due to magnetostriction can be included in the expression for the uniaxial anisotropy by appropriately adjusting the value of the anisotropy constant [20]. The surface magnetocrystalline anisotropy energy E_{Ks} is given by,

$$E_{Ks} = \int dS\frac{1}{2}(\hat{\alpha} \bullet \hat{n})^2$$

where the integration is along the (line increment dS in 2-D or a surface increment in 3-D) boundary at the film surfaces. The symmetry of the surface anisotropy energy was determined by Rado [21,22].The self-magnetostatic field energy E_s can be represented in a number of equivalent forms, but for these purposes the most convenient representation is

$$E_s = -\int dV\frac{1}{2}\vec{H}_s \bullet \hat{\alpha} M_s$$

where the self-field $\mathbf{H}_s$ is determined from the negative gradient of the scalar magnetic potential,

$$\vec{H} = -\nabla\phi$$

The magnetic scaler potential ϕ satisfies

$$\nabla^2\phi = 4\pi M_s \nabla \bullet \hat{\alpha}$$

inside the ferromagnet, and LaPlace's equation outside of the ferromagnet,

$$\nabla^2\phi' = 0$$

and at the surface $\varphi = \varphi'$ and

$$-\frac{d\phi}{dz} + 4\pi M_s\gamma = -\frac{d\phi}{dz}$$

in the two-dimensional case for example. The regularity of ϕ' at infinity is also required. This can be guaranteed by solving for the potential using Green's function methods. The calculation of this self- field energy is the most computationally intensive aspect of solving the micromagnetic equations. The external field energy E_h for an applied field of $\mathbf{H}_o$ is simply given as

$$E_h = -\int dV\vec{H}_o \bullet \hat{\alpha} M_s$$

To calculate the magnetic microstructure in ferromagnets, the time evolution of a magnetization configuration inside a ferromagnet, which is described by the Landau-Lifshitz-Gilbert equation, must be solved. The Landau-Lifshitz-Gilbert equation has been examined experimentally and theoretically [28,29,32,81,82], and found to yield an accurate description of the time evolution of a magnetic moment of fixed magnitude in a magnetic field. This equation has the following form.

$$\vec{dM}/dt = -\frac{\gamma}{1+\alpha^2}\vec{M}\times\vec{H}_{eff} - \frac{\gamma\alpha}{(1+\alpha^2)M_s}\vec{M}\times(\vec{M}\times\vec{H}_{eff})$$

Here, the gyromagnetic frequency $\gamma = g\omega_e/2$ is determined from the free electron value of ω_e and the spectroscopic splitting factor, g = 2. The gyromagnetic frequency γ, the damping parameter α and the magnitude of the effective fields determine the time scales of interest. For time domain simulations, the free electron gyromagnetic frequency of $\gamma = 1.78 \times 10^7$ (Oe sec-1) is used. The damping parameter α is not well known. Values of α between 0.005 and 2.0 have been used to solve LLG. The damping parameter was not found to change the equilibrium magnetization configurations in domain walls in uniform ferromagnetic systems [23]. The effective magnetic field on each magnetic moment is determined from the total system energy E_{tot} as

$$\vec{H}_{eff} = -\partial E_{tot}/\partial(M_s\hat{\alpha})$$

The effective magnetic field incorporates all the effects of exchange, anisotropy, external fields and demagnetizing fields. For the analysis of the equilibrium micromagnetic structure, the differential equation need not be integrated directly. Instead, notice that, for an equilibrium magnetization distribution, dM/dt = 0, which implies that the effective field, $\mathbf{H}_{eff}$, must be parallel to the magnetization **M**. The magnetization configuration can be relaxed iteratively by positioning each magnetization vector (almost) along the effective field vector direction throughout the mesh. The initial condition can be selected to provide a head start for the iteration procedure. When the largest residual of a single value of $(\mathbf{M}\times\mathbf{H}_{eff})/|\mathbf{M}||\mathbf{H}_{eff}|$ decreases below a convergence minimum, the iteration process is stopped. The convergence minimum for terminating the calculation is the value of the largest relative change in the largest component of the direction cosines. This value will depend upon the size of the mesh and on the closeness to a magnetization change, such as the reorientation close to the coercive field in a hysteresis loop calculation. Equilibrium domain wall configurations determined from this energy minimization scheme agree extremely well with configurations determined by solving the Landau-Lifshitz-Gilbert equation directly [23]. For equilibrium configurations for uniform systems, the more economical energy minimization scheme can be used to determine equilibrium configurations. For more complex systems, or in the presence on grain boundaries, which may serve as nucleation sites, the solution of the Landau-Lifshitz-Gilbert equation is necessary for accurate results [18,19].

The content of this section has been extracted and slightly altered from the original version published in a section of Micromagnetics of 180 Degree Domain Walls at Surfaces, M.R. Scheinfein, J. Unguris, J.L. Blue, K.J. Coakley, D.T. Pierce, R.J. Celotta, P.J. Ryan, Phys. Rev. B43(4), 3395 (1991).

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CHAPTER 4

LOADING AND SAVING FILES

FILE TYPES

LLG Micromagnetics Simulator supplies you with sample files in each format, as well as master input files that contain all of the start-up information necessary for initiating an LLG calculation. These files are loaded or saved at different points in the input, simulation and review phases. The files are either ASCII or binary; ASCII files can be edited in LLG's File Editor or Microsoft's NotePad. The input pages use the standard Windows Explorer interface to search for all files

Type of Data	File Format	Input/Output	Access
Bitmap	*.bmp	Output	Toolbar and Drop-down Me
Input Specifications	*.llg_param	Input	Input Control
Direction Cosine	*.llg_dom	Input/Output	Input Control
Convergence Data	*.llg_conv	Output	Input Control
Material Properties	*.llg_material	Input/Output	Material Properties
Pos. Dependent Mag. Fields	*.llg_inputhfield	Input/Output	Boundary Conditions
Hysteresis Field Profile	*.llg_hysfield	Input/Output	Hysteresis
Hysteresis Field & Mag.	*.llg_hys	Output	Hysteresis
Magnetization Masks	*.llg_mask	Input/Output	Mask and View
Magnetic Field	*.llg_hfield	Output	Views
Graphical Animation (Movies)	*.llg_movie	Input/Output	Movie Playback
Position Dependent Parameters	*.llg_postion	Input/Output	Position Dependent
Color Map File	*.llg_colormap	Input/Output	Color Wheel/Index
Shape File	*.llg_shape	Input/Output	Position Dependent

FIGURE 2. LLG File Types

BITMAP: *.BMP

These binary files can be saved through the Tool Bar or the LLG Drop-down Menu and are standard Windows bitmap formatted files. The contents of the OpenGL window can be captured and stored in a file for presentation or later use.

INPUT SPECIFICATIONS: *.LLG_PARAM

These ASCII files can be loaded and saved through the read and save **Read Input, Save v1 Input** and **Save v2 Input** buttons in the LLG Main Input Sheet. These are formatted files that can be edited with LLG's File Editor or a word processor, such as Microsoft's NotePad.

- **Loading**

  Data that has been loaded or saved in an *.llg_param file in ASCII format can be reloaded at a later time. These files contain the input specifications for all parameters, including layers. As such, loading parameters from a file saves time in the input phase; storing parameters to a file can save time by reusing them in the future.

- **Saving**

  If you have entered data through the LLG Input Sheet and its pages, as opposed to loading a file, it is highly recommended that you specify a *.llg_param file in which to store the ASCII start-up file. Save v1 and Save v2 options differentiate between v1 and v2 compatible input files. V2 will read v1 files, but version 1 will not read v2 files.

DIRECTION COSINES: *.LLG_DOM

These files can be loaded and saved through the **Angle Config** button in the Main Input Page or through the **Input File Name** button in the Initialization Page. These are ASCII files that contain the direction cosines for every element in the array.

If you start LLG by opening a *.llg_param file using the **Input Params** button, the prefix of the file you load will be appended by the *.llg_dom suffix and the output file will be written. Use this page if you wish to specify another name or to load an existing configuration to seed a new computation.

- **Loading**

  Loading these angles from a file allows you to start with any predefined magnetization distribution or to continue a computation that may have been terminated prematurely. If the loaded file does not have the same discretization as the problem you wish to run, you will be prompted to indicate whether or not you want to interpolate the old data onto the new grid. In addition, you can explore the effect of changing input parameters or other input specifications on a particular equilibrium magnetization structure.

- Saving

  Saving these angles to a file, which LLG requires, allows you to record the final equilibrium magnetization distribution. By default, these angles are saved for each computation. The default name is either the input prefix of the loaded *.LLG file or the loaded *.llg_param ASCII file with an .llg_dom suffix. If an alternative name is desired, this page confirms the new name. If no name is selected, the program prompts you for an acceptable name before you enter the simulation phase of the computation.

CONVERGENCE DATA: *.LLG_CONV

These ASCII files can be saved through the **Convergence** button in the **LLG Main Input Page**. Each file contains an iteration history and, optionally, the energy components at each end of each iteration cycle, the maximum residual energy, and the final equilibrium magnetization energy. If you start LLG by opening a *.llg_param file using the Input Params button, the prefix of the file you load will be appended by the *.llg_conv suffix and the output file will be written. If you wish to specify another name, use this **Convergence** button.

Default Setting: By default, the **Save Conv. Details** check box is ***NOT*** selected. In this mode, the energies are not written to the file at each iteration step. Only the final energy is saved. If you check the **Save Conv. Details** box, the system energy and its components are written to the file at each functional iteration or time step. Normal operation does not require this, although it is useful when you want to view the iteration history of the distribution of energies, exchange, anisotropy, dipolar and external field components. The cost is that a huge file is being constantly accessed.

MATERIAL PROPERTIES: *.LLG_MATERIAL

These files can be loaded and saved through the **Materials Page**. These are ASCII files that are in a database from which you can load the properties of materials or save the properties of materials that you have input.

POSITION-DEPENDENT MAGNETIC FIELDS: *.LLG_INPUTHFIELD

These files can be loaded and saved through the **Boundary Page**. These are ASCII input files for specifying non-uniform external fields.

HYSTERESIS FIELD PROFILE: *.LLG_HYSFIELD:

These files can be saved through the **Hysteresis Page**. These are ASCII input files that contain a field profile for any hysteresis loop.

HYSTERESIS FIELD AND MAGNETIZATION: *.LLG_HYS

These files can be loaded and saved through the **Hysteresis Pages**. These are ASCII output files that record the fields and magnetization at each point in the hysteresis loop.

MAGNETIZATION MASKS: *.LLG_MASK

These files can be saved through the **LLG Mask Editor** and **View Page** and in the Viewer Control. These are binary input files that load or save moments that have been masked (turned off).

MAGNETIC FIELD: *.LLG_HFIELD

These ASCII files can be saved in the **Views Page**. They are for saving the magnetic field and magnetic induction values.

GRAPHICAL ANIMATION (MOVIES): *.LLG_MOVIE

These binary files can be loaded through the **LLG Movie Page** accessed on the Tool Bar or the Drop-down menu and saved through the **Movies Page**. You can replay saved movies by clicking the Play button on the Tool Bar or by selecting the Replay Movies option under the Drop-down Menu. These are binary files that save the data for an entire simulation.

POSITION DEPENDENT PARAMETERS: *.LLG_POSITION

These binary files can be saved through the **Position Dependent Page**. These files record all the micromagnetic parameters at each discrete point.

COLOR MAP FILES: *.LLG_COLORMAP

These are ASCII files that store color wheels and color indices suitable for displaying data. The data are stored in ASCII format.

SHAPE FILES: *.LLG_SHAPE

These are ASCII files that store llg outline shapes used in the position dependent graphics tool and in the mask graphics tool. The data are stored in ASCII format.

USING THE LLG JOURNAL VIEWER

LLG Micromagnetics Simulator has a supplemental utility tool for generating catalogues of available LLG files. This tool, llgJournal.exe, is distributed with the LLG release. You can place the executable file in your LLG directory and create a desktop link to that file using the task bar manager.

You can use **LLG Journal Viewer** to view old journals, create new journals, or to examine the content of files on your disk. Although the journal files are stored in binary format, you can cut and paste either the journal log or the journal selections into any Windows-based editor, such as Wordpad and Microsoft Word, that supports the OLE embedding protocol. You can format your journal, including font size and type, color, and column width and spacing. Formatting information will be saved with your file.To activate llgJournal.exe, double click the icon or the task bar link and the **Journal Viewer Page** appears, as shown below.

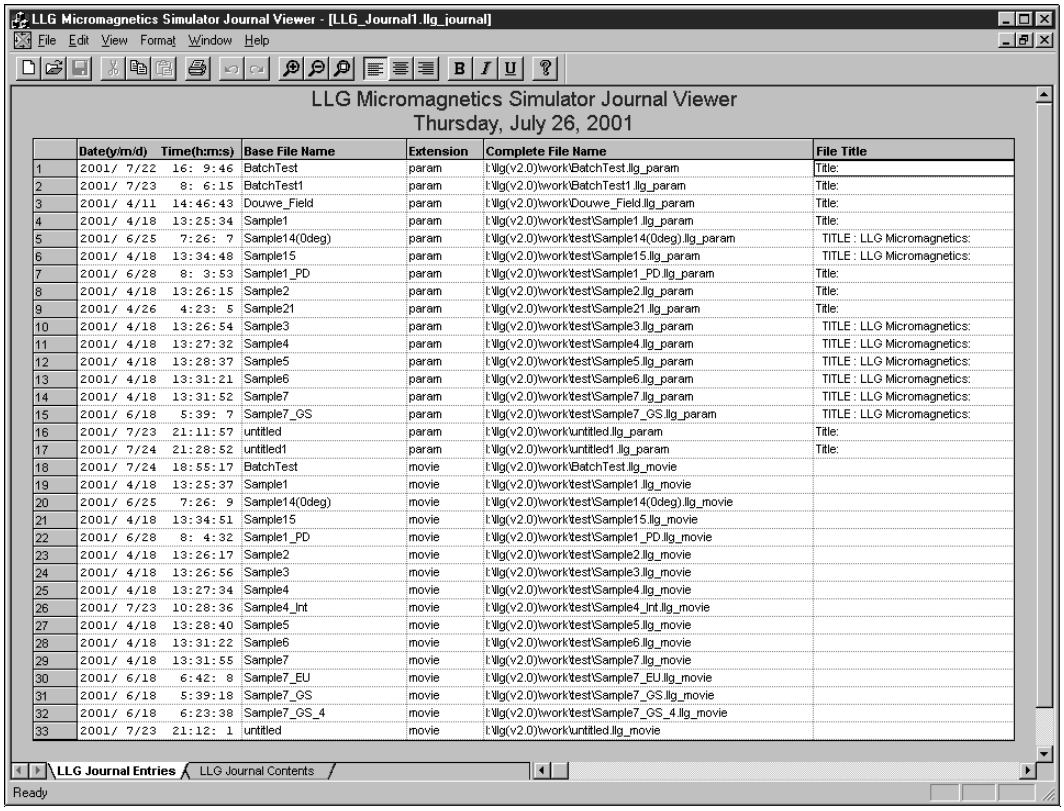
FIGURE 3. Journal Viewer Main Page

OPENING AN OLD JOURNAL FILE

To open and view an old journal file, either click the **Open File** icon or select **File**, **Open** from the drop down menu to activate the open file dialog. The suffix for journal files is *.llg_journal. Select the file that you want to view to it load it into a journal file. One journal file is shown below.

- The first left-hand column contains the numbered journal entries.
- The second column contains the file's date and time of creation.
- The third column contains the file path name.
- The last (fourth) column contains the title line extracted from the file, if it exists.The title is the character string that is entered at the top of the Main Input Page.

- **Print** the formatted journal file by clicking the **Print** icon.


LLG Micromagnetics Simulator Journal Viewer - [LLG_Journal1.llg_journal]
File Edit View Format Window Help
LLG Micromagnetics Simulator Journal Viewer
Thursday, July 26, 2001
LLG Journal Entries
LLG Journal Contents
Ready

	Date(y/m/d)	Time(h:m:s)	Base File Name	Extension	Complete File Name	File Title
1	2001/ 7/22	16: 9:46	BatchTest	param	I:\llg(v2.0)\work\BatchTest.llg_param	Title:
2	2001/ 7/23	8: 6:15	BatchTest1	param	I:\llg(v2.0)\work\BatchTest1.llg_param	Title:
3	2001/ 4/11	14:46:43	Douwe_Field	param	I:\llg(v2.0)\work\Douwe_Field.llg_param	Title:
4	2001/ 4/18	13:25:34	Sample1	param	I:\llg(v2.0)\work\test\Sample1.llg_param	Title:
5	2001/ 6/25	7:26: 7	Sample14(0deg)	param	I:\llg(v2.0)\work\test\Sample14(0deg).llg_param	TITLE : LLG Micromagnetics:
6	2001/ 4/18	13:34:48	Sample15	param	I:\llg(v2.0)\work\test\Sample15.llg_param	TITLE : LLG Micromagnetics:
7	2001/ 6/28	8: 3:53	Sample1_PD	param	I:\llg(v2.0)\work\test\Sample1_PD.llg_param	Title:
8	2001/ 4/18	13:26:15	Sample2	param	I:\llg(v2.0)\work\test\Sample2.llg_param	Title:
9	2001/ 4/26	4:23: 5	Sample21	param	I:\llg(v2.0)\work\test\Sample21.llg_param	Title:
10	2001/ 4/18	13:26:54	Sample3	param	I:\llg(v2.0)\work\test\Sample3.llg_param	TITLE : LLG Micromagnetics:
11	2001/ 4/18	13:27:32	Sample4	param	I:\llg(v2.0)\work\test\Sample4.llg_param	TITLE : LLG Micromagnetics:
12	2001/ 4/18	13:28:37	Sample5	param	I:\llg(v2.0)\work\test\Sample5.llg_param	TITLE : LLG Micromagnetics:
13	2001/ 4/18	13:31:21	Sample6	param	I:\llg(v2.0)\work\test\Sample6.llg_param	TITLE : LLG Micromagnetics:
14	2001/ 4/18	13:31:52	Sample7	param	I:\llg(v2.0)\work\test\Sample7.llg_param	TITLE : LLG Micromagnetics:
15	2001/ 6/18	5:39: 7	Sample7_GS	param	I:\llg(v2.0)\work\test\Sample7_GS.llg_param	TITLE : LLG Micromagnetics:
16	2001/ 7/23	21:11:57	untitled	param	I:\llg(v2.0)\work\untitled.llg_param	Title:
17	2001/ 7/24	21:28:52	untitled1	param	I:\llg(v2.0)\work\untitled1.llg_param	Title:
18	2001/ 7/24	18:55:17	BatchTest	movie	I:\llg(v2.0)\work\BatchTest.llg_movie	
19	2001/ 4/18	13:25:37	Sample1	movie	I:\llg(v2.0)\work\test\Sample1.llg_movie	
20	2001/ 6/25	7:26: 9	Sample14(0deg)	movie	I:\llg(v2.0)\work\test\Sample14(0deg).llg_movie	
21	2001/ 4/18	13:34:51	Sample15	movie	I:\llg(v2.0)\work\test\Sample15.llg_movie	
22	2001/ 6/28	8: 4:32	Sample1_PD	movie	I:\llg(v2.0)\work\test\Sample1_PD.llg_movie	
23	2001/ 4/18	13:26:17	Sample2	movie	I:\llg(v2.0)\work\test\Sample2.llg_movie	
24	2001/ 4/18	13:26:56	Sample3	movie	I:\llg(v2.0)\work\test\Sample3.llg_movie	
25	2001/ 4/18	13:27:34	Sample4	movie	I:\llg(v2.0)\work\test\Sample4.llg_movie	
26	2001/ 7/23	10:28:36	Sample4_Int	movie	I:\llg(v2.0)\work\test\Sample4_Int.llg_movie	
27	2001/ 4/18	13:28:40	Sample5	movie	I:\llg(v2.0)\work\test\Sample5.llg_movie	
28	2001/ 4/18	13:31:22	Sample6	movie	I:\llg(v2.0)\work\test\Sample6.llg_movie	
29	2001/ 4/18	13:31:55	Sample7	movie	I:\llg(v2.0)\work\test\Sample7.llg_movie	
30	2001/ 6/18	6:42: 8	Sample7_EU	movie	I:\llg(v2.0)\work\test\Sample7_EU.llg_movie	
31	2001/ 6/18	5:39:18	Sample7_GS	movie	I:\llg(v2.0)\work\test\Sample7_GS.llg_movie	
32	2001/ 6/18	6:23:38	Sample7_GS_4	movie	I:\llg(v2.0)\work\test\Sample7_GS_4.llg_movie	
33	2001/ 7/23	21:12: 1	untitled	movie	I:\llg(v2.0)\work\untitled.llg_movie	

FIGURE 4. Journal Viewer: Journal Entries Page

SORTING JOURNAL ENTRIES

You can sort LLG journal entries by double clicking the column header.

- To sort by date, double click the **Date** header.
- To sort by file name, double click the **Base File Name** header.
- To sort the list by title, double click the **File Title** header. A second double click sorts any list in inverse order.

EXAMINING JOURNAL ENTRIES

Once you have compiled a journal, you can use the list to examine the file's contents. Using the mouse, right double-click the left-most column of the row that contains the file that you wish to view. The contents of that file (if it is an ascii

file) will be loaded into the **LLG Journal Contents** window (tabbed at bottom), as shown below. **Print** the formatted journal contents by clicking the Print icon.

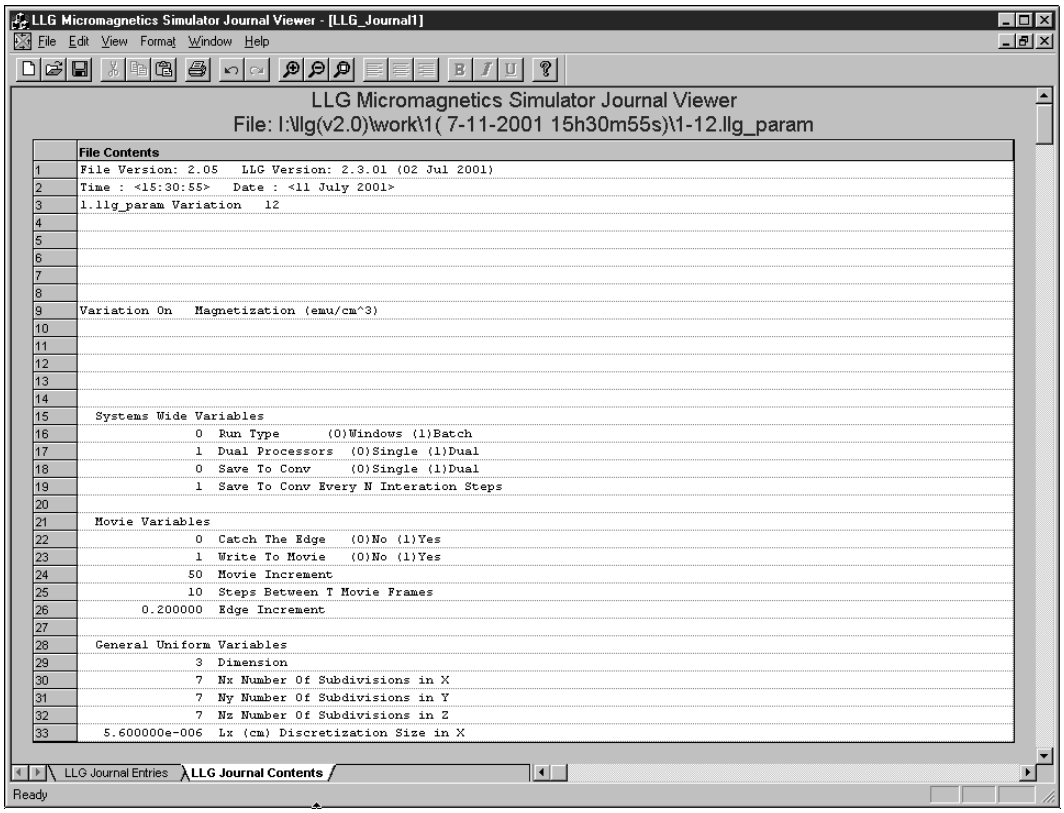

LLG Micromagnetics Simulator Journal Viewer - [LLG_Journal1]
File Edit View Format Window Help
LLG Micromagnetics Simulator Journal Viewer
File: I:\llg(v2.0)\work\1(7-11-2001 15h30m55s)\1-12.llg_param
File Contents
File Version: 2.05 LLG Version: 2.3.01 (02 Jul 2001)
Time : <15:30:55> Date : <11 July 2001>
1.llg_param Variation 12
Variation On Magnetization (emu/cm^3)
Systems Wide Variables
0 Run Type (0)Windows (1)Batch
1 Dual Processors (0)Single (1)Dual
0 Save To Conv (0)Single (1)Dual
1 Save To Conv Every N Interation Steps
Movie Variables
0 Catch The Edge (0)No (1)Yes
1 Write To Movie (0)No (1)Yes
50 Movie Increment
10 Steps Between T Movie Frames
0.200000 Edge Increment
General Uniform Variables
3 Dimension
7 Nx Number Of Subdivisions in X
7 Ny Number Of Subdivisions in Y
7 Nz Number Of Subdivisions in Z
5.600000e-006 Lx (cm) Discretization Size in X
LLG Journal Entries
LLG Journal Contents
Ready

FIGURE 5. Journal Viewer: Journal Contents Page

MODIFYING COMMENTS IN PARAMETER FILES

When a *.llg_param file is loaded into the **Journal Viewe**r, you can edit the title and the comment lines. This file can be saved to disk using the **File** pull down menu at the top left of the main window. The option of editing the file data or the journal itself is disabled.

CREATING A NEW JOURNAL

You can create a new journal at any time. Since llgJournal.exe can search any file system and compile any sequenced list that you like, you never have to worry about deleting or loosing your journal files. However, you can maintain a time snapshot of your LLG file system by keeping your generated *.llg_journal files as a record. To create a new journal,

click the **New File** icon in the task bar or select **File**, **New** from the file drop-down menu, which activates the journal generator, shown below.

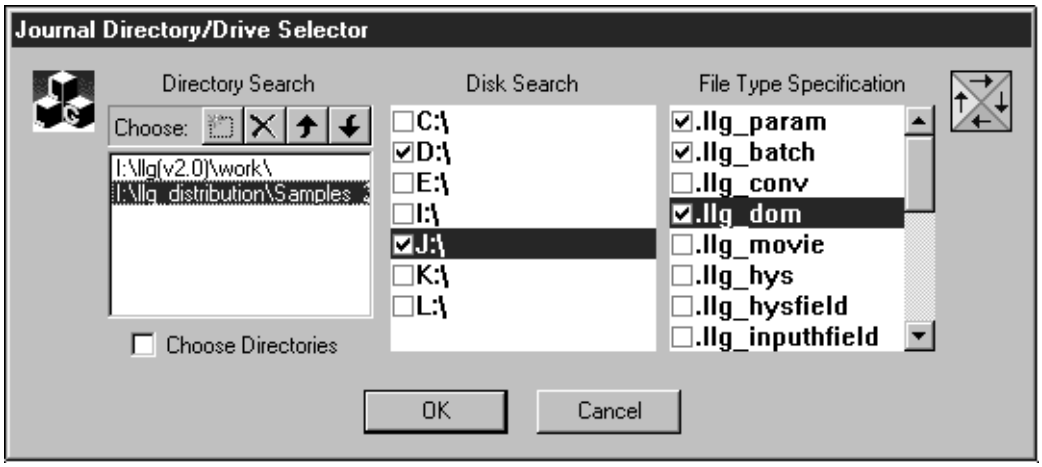


FIGURE 6. Journal Viewer: Journal Directory and Drive Selector

SPECIFYING FILE TYPE

You can select which file types to add to your journal by checking the appropriate box adjacent to the file type. Above, the selected file types include input (*.llg_param), batch (*.llg_batch) and domain (*.llg_dom) files. All LLG-specific file types can be archived in a journal.

SEARCHING DISKS OR DIRECTORIES

You can choose ***ONE*** of two possible search mechanisms.

1. If you have specific directories that you want to generate journal files for, check the **Choose Directories** box and use the **Directory Search** tool to add the directories to the list. Above, two directories have been added to the list. There is no limit on the number of directories that you can add to the list.
2. Alternatively, you can select entire disk systems to scan for LLG files. Above, disks D:\ and J:\ have been selected. The Journal Viewer scans your system for ***HARD DRIVES ONLY***. It will not scan CDs, IOMEGA type drives, or the network. In other words, LLG only scans your local hard drives for LLG files. Once you have specified the file types and search paths, click the **OK** button to generate the journal. You will hear the disk being searched; the length of the search depends on how many disks you specify and on the speed of your disk drive.

SUMMARY OF INPUT AND OUTPUT FILE FORMATS OF V1

Position-Dependent Magnetic Fields: *.llg_inputhfield

```
Type:       External Position Dependent Field File
```
Format: Formatted (ASCII)

Where: Boundary Condition Dialog

Prompt: Read H-File; Write H-File

Suffix: *.llg_inputhfield

Variables: NX number along x-direction

NY number along y-direction

NZ number along z-direction

HX field in Oe along x-direction

HY field in Oe along y-direction

HZ field in Oe along z-direction

```
    READ (UNIT,1) NX,NY,NZ
1   FORMAT(3I5)

     DO 100 I = 1,NX
     DO 100 J = 1,NY
     DO 100 K = 1,NZ
100  READ (UNIT,2) HX(I,J,K), HY(I,J,K), HZ(I,J,K)
FORMAT(3F15.3)
```

Material Properties: *.llg_material

Type: External Materials Data Base File

Format: Formatted (ASCII)

Where: Materials Dialog

Prompt: Open Data Base; Write Data Base

Suffix: *.llg_material

Variables: NUM number of database entries

DB_LABEL identifying label for material

DB_CA exchange constant in u-erg/cm

DB_MS saturation magnetization in emu/cm^3

DB_CK uniaxial anisotropy in erg/cm^3

DB_CKC cubic anisotropy in erg/cm^3

DC_CS surface anisotropy in erg/cm^2

DB_RHO resistivity in u-ohm/cm

DB_AMR anisotropy magnetoresistance

DB_ATYPE anisotropy direction for uniaxial case

```
    DO 100 I = 1,NUM
    READ(UNIT,1) DB_LABEL(I),DB_CA(I), DB_MS(I), DB_CK(I), DB_CKC(I), &
```

```
      DB_CS(I, DB_RHO(I), DB_AMR(I), DB_ATYPE(I)
100   CONTINUE
1     FORMAT( A20, 7(1X,D15.5),1X, A1)
```

Hysteresis Field Profile: *.llg_hysfield

Type: External Hysteresis Field File
Format: Formatted (ASCII)
Where: Hysteresis Dialog
Prompt: Read Input File; Write Input File
Suffix: *.llg_hysfield
Variables: NHPTS number of hysteresis field points (NHPTS < 1025)
HX field in Oe along x-direction
HY field in Oe along y-direction
HZ field in Oe along z-direction

```
      READ (UNIT,1) NHPTS
1     FORMAT(I4)

      IF( NHPTS .GT. 1024) THEN
            NHPTS = 1024
            CALL READ_ERROR_HANDLER(-11)
     ENDIF

     DO 100 I= 1,NHPTS
100   READ (29,2) HX(I),HY(I),HZ(I)
FORMAT(3F10.2)
```

Coupling Tensors: *.llg_coup

Type: Demagnetization Coupling Tensor File
Format: Unformatted (BINARY)
Where: Input Dialog
Prompt: Read Self Energy Tensor; Write Self Energy Tensor
Suffix: *.llg_coup
Variables: NX (integer) number along x-direction
NY (integer) number along y-direction
NZ (integer) number along z-direction
ACOEF (double precision) coupling arrays constants

```
      READ (UNIT) NX,NY,NZ
     DO 100 M = 1,6
      DO 100 I = -NX,NX-1
      DO 100 J = -NY,NY-1
```

```
      DO 100 K = -NZ,NZ-1
100 READ (UNIT) ACOEF(M,I,J,K)
```

Graphical Animation: *.llg_movie

Type: LLG Movie File
Format: Unformatted (BINARY)
Where: Movie Dialog
Prompt: Load File
Suffix: *.llg_movie
Variables: IO_MOVIE_VER (integer) currently 6 identifier
NX (integer) number along x-direction
NY (integer) number along y-direction
NZ (integer) number along z-direction
HCOUNT (integer) number of movie frames
FRAME (integer) number of the frame
HX (double precision) hysteresis field in Oe along x-
HY (double precision) hysteresis field in Oe along y-
HZ (double precision) hysteresis field in Oe along z-
MX (double precision) remanence along x-direction
MY (double precision) remanence along y-direction
MZ (double precision) remanence along z-direction
HHYST (double precision) magnitude of field in Oe
MHYST (double precision) magnitude of remanence along field
MR_RES (double precision) resistance in ohms
MR_VOLT (double precision) voltage in volts
ANG_X (double precision) magnetization direction cosine x
ANG_Y (double precision) magnetization direction cosine y
ANG_Z (double precision) magnetization direction cosine z

```
      READ(UNIT) IO_MOVIE_VER,IO_MOVIE_VER,IO_MOVIE_VER,IO_MOVIE_VER
      READ(UNIT) NX, NY, NZ, HCOUNT

      DO 200 FRAME = 1,HCOUNT
      READ(UNIT) FRAME
      READ(UNIT) HX(FRAME), HY(FRAME), HZ(FRAME)
      READ(UNIT) MX(FRAME), MY(FRAME), MZ(FRAME)
      READ(UNIT) HHYST(FRAME), MHYST(FRAME),MR_RES(FRAME),MR_VOLT(FRAME)

     DO 100 I=1,NX
     DO 100 J=1,NY
     DO 100 K=1,NZ
100   READ(UNIT)ANG_X(I,J,K),ANG_Y(I,J,K),ANG_Z(I,J,K)
200   CONTINUE
```

Direction Cosines: *.llg_dom

Type: LLG Domain File
Format: Formatted (ASCII)
Where: Input Dialog and Saving Dialogs Throughout
Prompt: Read Input Angle Configuration; Write Input Angle Configuration
Suffix: *.llg_dom
Variables: NX number along x-direction
NY number along y-direction
NZ number along z-direction
ANG_X magnetization direction cosine along x-direction
ANG_Y magnetization direction cosine along y-direction
ANG_Z magnetization direction cosine along z-direction
II dummy index in x for file visualization assistance
JJ dummy index in y for file visualization assistance
KK dummy index in z for file visualization assistance

```
      READ(UNIT,1)NX,NY,NZ
1     FORMAT(3I3)

     DO 100 I=1,NX
     DO 100 J=1,NY
     DO 100 K=1,NZ
100   READ (UNIT,2)II,JJ,KK,ANG_X(I,J,K),ANG_Y(I,J,K),ANG_Z(I,J,K)
2     FORMAT(3i3,3E15.7)
```

Magnetization Masks: *.llg_mask

Type: LLG Mask File
Format: Unformatted (BINARY)
Where: View/Mask (Input Graphics) Dialog
Prompt: Save Mask; Read Mask; Hysteresis or Regular Mask
Suffix: *.llg_mask
Variables: NX (integer) number along x-direction
NY (integer) number along y-direction
NZ (integer) number along z-direction

```
      READ(UNIT)NX,NY,NZ

     DO 100 I=1,NX
     DO 100 J=1,NY
     DO 100 K=1,NZ
100   READ (UNIT) PICKER(I,J,K) or HYSTPICKER(I,J,K)
```

Hysteresis Field and Magnetization: *.llg_hys

Type: LLG Hysteresis Output File
Format: Formatted (ASCII)
Where: Hysteresis Dialog or Automatic Prompt
Prompt: Name Output File
Suffix: *.llg_hys
Variables: HCOUNT number of field points

```
     H field magnitude in Oe
```

M remanence along field
HX field in Oe along x-direction
HY field in Oe along y-direction
HZ field in Oe along z-direction
MX remanence along x-direction
MY remanence along y-direction
MZ remanence along z-direction
MR_RES resistance in ohms
MR_VOLT voltage in volts

```
      READ(UNIT,1)
1     FORMAT(' Hmag(Oe) Mmag/Ms  Hx(Oe)   Hy(Oe)   Hz(Oe)    Mx/Ms    My/Ms
              Mz/Ms    R(ohm)    V(mV)')
     DO 100 I = 1,HCOUNT
READ(UNIT,2) H(I),M(I),HX(I),HY(I),HZ(I),MX(I),MY(I),MZ(I),MR_RES(I),&
MR_VOLT(I)
2     FORMAT(F9.1, F9.3, 3F9.1, 3F9.3, 2F9.3)
```

SUMMARY OF INPUT AND OUTPUT FILE FORMATS OF V2

Mask Files

```
t_BOOL CDataIO::WriteMaskFile2_01(t_pChar pFileName, t_BOOL bAllocate)
{       t_Int nMaskSize,nIntSize,n[3];
        nMaskSize = m_nSize*sizeof(t_BOOL);
        nIntSize  = 3*sizeof(t_Int);
        // Open File
        if( !m_fileStdio.Open(pFileName, CStdioFile::modeWrite | CStdioFile::modeCreate, &m_fileException))
        {               FileExceptionHandler(&m_fileException);
                        return FALSE;
        }
        // Write Header String
        m_fileStdio.Write(&m_cVersion,64*sizeof(t_Char));
        // Write Integers
        n[0] = m_pLLG->m_nX;n[1] = m_pLLG->m_nY;n[2] = m_pLLG->m_nZ;
        m_fileStdio.Write(&n,nIntSize);
        // Write Mask
```

```
	m_fileStdio.Write(m_pLLG->m_pMask,nMaskSize);
	// Success
	m_fileStdio.Close();
	return TRUE;
}
```

Dom Files

```
t_BOOL CDataIO::WriteAngleFile2_01(t_pChar pFileName, t_BOOL bAllocate)
{	t_Int nArraySize,nIntSize;
	nArraySize = m_nSize*sizeof(t_Double);
	nIntSize  = 3*sizeof(t_Int);

	// Open File
	if( !m_fileStdio.Open(pFileName, CStdioFile::modeWrite |  CStdioFile::modeCreate,  &m_fileException))
	{		FileExceptionHandler(&m_fileException);
			return FALSE;
	}
	m_fileStdio.WriteString(m_strVersion + "\n\0");
	m_strBuffer1.Format("%6i%6i%6i",m_pLLG->m_nX,m_pLLG->m_nY,m_pLLG->m_nZ);
	m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
	// Write Data
	for(t_Int k = 0; k < m_pLLG->m_nZ; k++)
		for(t_Int j = 0; j < m_pLLG->m_nY; j++)
			for(t_Int i = 0; i < m_pLLG->m_nX; i++)
			{	m_nOffset = OffSetComputer(i,j,k);
				m_strBuffer1.Format("%15e%15e%15e%15e%15e%15e",
				m_pLLG->m_pX[m_nOffset], m_pLLG->m_pY[m_nOffset],
				m_pLLG->m_pZ[m_nOffset],
				m_pLLG->m_pAX[m_nOffset],m_pLLG->m_pAY[m_nOffset],
				m_pLLG->m_pAZ[m_nOffset]);
			m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
		}
	// Success
	m_fileStdio.Close();
	return TRUE;
}
```

H-Field Files

```
t_BOOL CDataIO::WriteHFieldFile2_01(t_pChar pFileName, t_BOOL bAllocate)
{	// Open File
	if( !m_fileStdio.Open(pFileName, CStdioFile::modeWrite |  CStdioFile::modeCreate,  &m_fileException))
		{		FileExceptionHandler(&m_fileException);
				return FALSE;
		}
	// Write Header String
```

```
	m_fileStdio.WriteString(m_strVersion + "\n\0");
	m_strBuffer1.Format("%6i%6i%6i",m_pLLG->m_nX,m_pLLG->m_nY,m_pLLG->m_nZ);
	m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
	// Write Data
	for(t_Int k = 0; k < m_pLLG->m_nZ; k++)
		for(t_Int j = 0; j < m_pLLG->m_nY; j++)
			for(t_Int i = 0; i < m_pLLG->m_nX; i++)
			{	m_nOffset = OffSetComputer(i,j,k);
				m_strBuffer1.Format("%15e%15e%15e%15e%15e%15e",
					m_pLLG->m_pX[m_nOffset], m_pLLG->m_pY[m_nOffset],
					m_pLLG->m_pZ[m_nOffset],
					m_pLLG->m_pHbcX[m_nOffset],m_pLLG->m_pHbcY[m_nOffset],
					m_pLLG->m_pHbcZ[m_nOffset]);
				m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
			}
	m_fileStdio.Close();
	return TRUE;
}
```

Arbitrary H-Field Files

```
t_BOOL CDataIO::WriteArbitraryFieldFile2_01(t_pChar pFileName, t_pDouble pX, t_pDouble pY, t_pDouble pZ)
{	// Open File
	if( !m_fileStdio.Open(pFileName, CStdioFile::modeWrite | CStdioFile::modeCreate, &m_fileException))
		{		FileExceptionHandler(&m_fileException);
				return FALSE;
		}
	// Write Header String
	m_fileStdio.WriteString(m_strVersion + "\n\0");
	m_strBuffer1.Format("%6i%6i%6i",m_pLLG->m_nX,m_pLLG->m_nY,m_pLLG->m_nZ);
	m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
	// Write Data
	for(t_Int k = 0; k < m_pLLG->m_nZ; k++)
		for(t_Int j = 0; j < m_pLLG->m_nY; j++)
			for(t_Int i = 0; i < m_pLLG->m_nX; i++)
			{	m_nOffset = OffSetComputer(i,j,k);
				m_strBuffer1.Format("%15e%15e%15e%15e%15e%15e",
					m_pLLG->m_pX[m_nOffset], m_pLLG->m_pY[m_nOffset],
						m_pLLG->m_pZ[m_nOffset],
						pX[m_nOffset],pY[m_nOffset],pZ[m_nOffset]);
				m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
			}


	m_fileStdio.Close();
```

```
	return TRUE;
}
```

Hysteresis Field Files

```
t_BOOL CDataIO::WriteHysFieldFile2_01(t_pChar pFileName, t_BOOL bAllocate)
{	// Open File
	if( !m_fileStdio.Open(pFileName, CStdioFile::modeWrite | CStdioFile::modeCreate,  &m_fileException))
	{		FileExceptionHandler(&m_fileException);
			return FALSE;
	}
	// Write Header String
	m_fileStdio.WriteString(m_strVersion + "\n\0");
	m_strBuffer1.Format("%4i",m_pLLG->m_nHysHpts);
	m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
	for(t_Int i = 0; i < m_pLLG->m_nHysHpts; i++)
	{	m_strBuffer1.Format("%10.2f%10.2f%10.2f",m_pLLG->m_dHysHLoop[0][i],
					m_pLLG->m_dHysHLoop[1][i], m_pLLG->m_dHysHLoop[2][i]);
		m_strBuffer1 = m_strBuffer1;
		m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
	}
	m_fileStdio.Close();
	return TRUE;
}
```

Current Files

```
t_BOOL CDataIO::WriteCurFile2_01(t_pChar pFileName, t_BOOL bAllocate)
{	// Open File
	if( !m_fileStdio.Open(pFileName, CStdioFile::modeWrite | CStdioFile::modeCreate,  &m_fileException))
	{		FileExceptionHandler(&m_fileException);
			return FALSE;
	}
	// Write Header String
	m_fileStdio.WriteString(m_strVersion + "\n\0");
	m_strBuffer1.Format("%4i",m_pLLG->m_nCurHpts);
	m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
	for(t_Int i = 0; i < m_pLLG->m_nCurHpts; i++)
	{	m_strBuffer1.Format("%10.2f",m_pLLG->m_dCurLoop[i]);
		m_strBuffer1 = m_strBuffer1;
		m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
	}
	m_fileStdio.Close();
	return TRUE;
}
```

Materials Database Files

```
t_BOOL CDataIO::WriteMatBaseFile2_01(t_pChar pFileName, t_BOOL bAllocate)
```

```
{       // Open File
        if( !m_fileStdio.Open(pFileName, CStdioFile::modeWrite |  CStdioFile::modeCreate,  &m_fileException))
        {               FileExceptionHandler(&m_fileException);
                        return FALSE;
        }
        // Write Header String
        m_fileStdio.WriteString(m_strVersion + "\n\0");
        m_strBuffer1.Format("%4i",(t_Int) bAllocate);
        m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
        for(t_Int i = 0; i <= (t_Int) bAllocate; i++)
        {       m_strBuffer1 = "                    ";
                for(t_Int j = 0; j < 20; j++)
                        m_strBuffer1.SetAt(j,m_pLLG->m_MatBaseLabel[i][j]);
                m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
                m_strBuffer1.Format("%10.3f",m_pLLG->m_MatBaseA[i]);
                m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
                m_strBuffer1.Format("%10.3f",m_pLLG->m_MatBaseMs[i]);
                m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
                m_strBuffer1.Format("%10.3f",m_pLLG->m_MatBaseKu2[i]);
                m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
                m_strBuffer1.Format("%10.3f",m_pLLG->m_MatBaseKu4[i]);
                m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
                m_strBuffer1.Format("%10.3f",m_pLLG->m_MatBaseKc[i]);
                m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
                m_strBuffer1.Format("%10.3f",m_pLLG->m_MatBaseKs[i]);
                m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
                m_strBuffer1.Format("%10.3f",m_pLLG->m_MatBaseRho[i]);
                m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
                m_strBuffer1.Format("%10.3f",m_pLLG->m_MatBaseAMR[i]);
                m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
                m_strBuffer1.Format("%2i",(t_Int) m_pLLG->m_MatBaseKType[i]);
                m_fileStdio.WriteString(m_strBuffer1 + "\n\0");
        }
        m_fileStdio.Close();
        return TRUE;
}
```

Position Dependent Parameter Files

```
t_BOOL CDataIO::WritePosDepFile2_01(t_pChar pFileName, t_BOOL bAllocate)
{       t_Int nMaskSize,nArraySize, nExchangeSize, nIntSize,n[3];
        nMaskSize = m_nSize*sizeof(t_BOOL);
        nArraySize = m_nSize*sizeof(t_Double);
        nExchangeSize = (m_nX+2)*(m_nY+2)*(m_nZ+2)*sizeof(t_Double);
        nIntSize  = 3*sizeof(t_Int);
```

```
// Open File
if( !m_fileStdio.Open(pFileName, CStdioFile::modeWrite |  CStdioFile::modeCreate, &m_fileException))
{                   FileExceptionHandler(&m_fileException);
                    return FALSE;
}
// Write Header String
m_fileStdio.Write(&m_cVersion,64*sizeof(t_Char));
// Write Integers
n[0] = m_nX;n[1] = m_nY;n[2] = m_nZ;
m_fileStdio.Write(&n,nIntSize);
// Write PosDep
if(m_bDoProgress)
{       m_dTotal = 100;
        m_nOffset = 0;
        m_pProgress->StartProgress(0,100,"Writing File");
        m_pProgress->SetProgressPos(0);
}

m_fileStdio.Write(m_pLLG->m_pPosDepMagnetization,nArraySize);// Magnetization
        m_nOffset+=3;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepExchange_X,nExchangeSize);// X Directed Exchange
        m_nOffset+=4;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepExchange_Y,nExchangeSize);// Y Directed Exchange
        m_nOffset+=3;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepExchange_Z,nExchangeSize);// Z Directed Exchange
        m_nOffset+=4;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepUniaxial_2,nArraySize);// Uniaxial Anisotropy 2 order
        m_nOffset+=3;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepUniaxial_4,nArraySize);// Uniaxial Anisotropy 4 order
        m_nOffset+=4;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepCubic,nArraySize);// Cubic Anisotropy
        m_nOffset+=3;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepHpin_X,nArraySize);// X Pinned H-Field
        m_nOffset+=4;
        if(m_bDoProgress) UpdateProgressBar();
```

```
m_fileStdio.Write(m_pLLG->m_pPosDepHpin_Y,nArraySize);// Y Pinned H-Field
        m_nOffset+=3;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepHpin_Z,nArraySize);// Z Pinned H-Field
        m_nOffset+=4;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepAnisotropyType,nMaskSize);// Anisotropy Type
        m_nOffset+=3;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepUniaxialAxis_X,nArraySize);// Uniaxial X-axis
        m_nOffset+=3;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepUniaxialAxis_Y,nArraySize);// Uniaxial Y-axis
        m_nOffset+=4;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepUniaxialAxis_Z,nArraySize);// Uniaxial Z-axis
        m_nOffset+=3;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepCubicAxis_1_X,nArraySize);// Cubic X-axis1
        m_nOffset+=4;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepCubicAxis_1_Y,nArraySize);// Cubic Y-axis1
        m_nOffset+=4;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepCubicAxis_1_Z,nArraySize);// Cubic Z-axis1
        m_nOffset+=3;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepCubicAxis_2_X,nArraySize);// Cubic X-axis2
        m_nOffset+=4;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepCubicAxis_2_Y,nArraySize);// Cubic Y-axis2
        m_nOffset+=3;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepCubicAxis_2_Z,nArraySize);// Cubic Z-axis2
        m_nOffset+=4;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepCubicAxis_3_X,nArraySize);// Cubic X-axis3
        m_nOffset+=3;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepCubicAxis_3_Y,nArraySize);// Cubic Y-axis3
        m_nOffset+=4;
        if(m_bDoProgress) UpdateProgressBar();
m_fileStdio.Write(m_pLLG->m_pPosDepCubicAxis_3_Z,nArraySize);// Cubic Z-axis3
```

```
		m_nOffset+=3;
		if(m_bDoProgress) UpdateProgressBar();
	m_fileStdio.Write(m_pLLG->m_pPosDepRho,nArraySize);// Resistivity
		m_nOffset+=4;
		if(m_bDoProgress) UpdateProgressBar();
	m_fileStdio.Write(m_pLLG->m_pPosDepAMR,nArraySize);// AMR Coefficient
		m_nOffset+=3;
		if(m_bDoProgress) UpdateProgressBar();
	m_fileStdio.Write(m_pLLG->m_pPosDepGMR,nArraySize);// BiLinear GMR Coefficient
		m_nOffset+=4;
		if(m_bDoProgress) UpdateProgressBar();
	m_fileStdio.Write(m_pLLG->m_pPosDep_BiLinear,nArraySize);// BiLinear GMR Coefficient
		m_nOffset+=3;
		if(m_bDoProgress) UpdateProgressBar();
	m_fileStdio.Write(m_pLLG->m_pPosDep_BiQuadratic,nArraySize);// BiQuadratic GMR Coefficient
		m_nOffset+=3;
		if(m_bDoProgress) UpdateProgressBar();
	m_fileStdio.Write(m_pLLG->m_pPosDepColor,m_nSize*sizeof(COLORREF));// Color Table Key
		if(m_bDoProgress)m_pProgress->StopProgress();
	// Success
	m_fileStdio.Close();
	return TRUE;
}
```

Current Mask

```
t_BOOL CDataIO::WriteCurrentMaskFile2_01(t_pChar pFileName, t_BOOL bAllocate)
{	t_Int nMaskSize,nIntSize,n[3];
	nMaskSize = m_nSize*sizeof(t_BOOL);
	nIntSize  = 3*sizeof(t_Int);
	// Open File
	if( !m_fileStdio.Open(pFileName, CStdioFile::modeWrite | CStdioFile::modeCreate,  &m_fileException))
	{		FileExceptionHandler(&m_fileException);
			return FALSE;
	}
	// Write Header String
	m_fileStdio.Write(&m_cVersion,64*sizeof(t_Char));
	// Write Integers
	n[0] = m_nX;n[1] = m_nY;n[2] = m_nZ;
	m_fileStdio.Write(&n,nIntSize);
	// Write Mask
	m_fileStdio.Write(m_pLLG->m_pCurMask,nMaskSize);
	// Success
	m_fileStdio.Close();
	return TRUE;
```

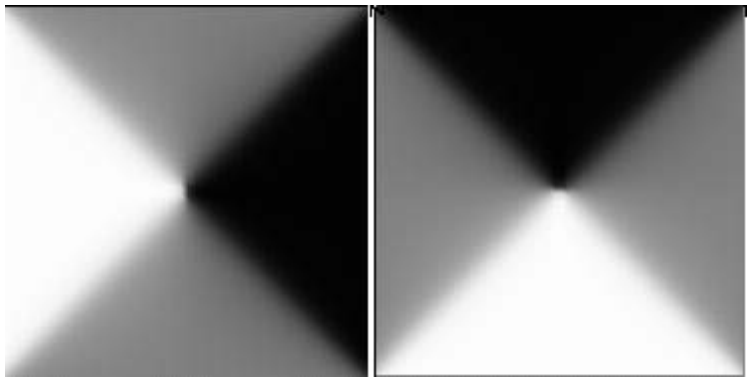
```
}
```

Movie Files

```
t_BOOL CDataIO::OpenMovieFile()
{       // Open File
        if( !m_fileMovie.Open(m_pLLG->m_pFileMaster->IO_WriteMovie, CFile::modeWrite |CFile::modeCreate,
                                &m_fileException))
        {               FileExceptionHandler(&m_fileException);
                                return FALSE;
                }
        // Write Header String
        m_fileMovie.Write(&m_cVersion,64*sizeof(t_Char));
        // Write Size
        m_fileMovie.Write(&m_pLLG->m_nX,sizeof(t_Int));
        m_fileMovie.Write(&m_pLLG->m_nY,sizeof(t_Int));
        m_fileMovie.Write(&m_pLLG->m_nZ,sizeof(t_Int));
        // Place Holder for Size
        m_fileMovie.Write(&m_pLLG->m_nZ,sizeof(t_Int));
        // Write Dimensions
        m_fileMovie.Write(&m_pLLG->m_X, sizeof(t_Double));
        m_fileMovie.Write(&m_pLLG->m_Y, sizeof(t_Double));
        m_fileMovie.Write(&m_pLLG->m_Z, sizeof(t_Double));
        m_fileMovie.Write(&m_pLLG->m_dX, sizeof(t_Double));
        m_fileMovie.Write(&m_pLLG->m_dY, sizeof(t_Double));
        m_fileMovie.Write(&m_pLLG->m_dZ, sizeof(t_Double));
        // Write Positions
        m_fileMovie.Write(m_pLLG->m_pX, m_nSize*sizeof(t_Double));
        m_fileMovie.Write(m_pLLG->m_pY, m_nSize*sizeof(t_Double));
        m_fileMovie.Write(m_pLLG->m_pZ, m_nSize*sizeof(t_Double));
        return TRUE;

}
t_BOOL CDataIO::WriteMovieFile(t_Int ii, t_Double dTime)
{       // Hcount
        m_fileMovie.Write(&m_pLLG->m_nHysHcount, sizeof(t_Int));
        // CMax
        m_fileMovie.Write(&dTime, sizeof(t_Double));
        // HLoop
        m_fileMovie.Write(&m_pLLG->m_pStatistics->m_pHx[ii], sizeof(t_Double));
        m_fileMovie.Write(&m_pLLG->m_pStatistics->m_pHy[ii], sizeof(t_Double));
        m_fileMovie.Write(&m_pLLG->m_pStatistics->m_pHz[ii], sizeof(t_Double));
        // MLoop
        m_fileMovie.Write(&m_pLLG->m_pStatistics->m_pMx[ii], sizeof(t_Double));
        m_fileMovie.Write(&m_pLLG->m_pStatistics->m_pMy[ii], sizeof(t_Double));
```

```
        m_fileMovie.Write(&m_pLLG->m_pStatistics->m_pMz[ii], sizeof(t_Double));
        // HMag and Remanence Resistance and Voltage
        m_fileMovie.Write(&m_pLLG->m_dHysHField[ii], sizeof(t_Double));
        m_fileMovie.Write(&m_pLLG->m_dHysMRem[ii], sizeof(t_Double));
        m_fileMovie.Write(&m_pLLG->m_dMRResistance[ii], sizeof(t_Double));
        m_fileMovie.Write(&m_pLLG->m_dMRVoltage[ii], sizeof(t_Double));
        // Angles
        m_fileMovie.Write(m_pLLG->m_pAX, m_nSize*sizeof(t_Double));
        m_fileMovie.Write(m_pLLG->m_pAY, m_nSize*sizeof(t_Double));
        m_fileMovie.Write(m_pLLG->m_pAZ, m_nSize*sizeof(t_Double));
        return TRUE;
}
t_BOOL CDataIO::CloseMovieFile()
{       m_fileMovie.Seek( 64+3*sizeof(t_Int), CFile::begin);
        m_fileMovie.Write(&m_pLLG->m_nHysHcount,sizeof(t_Int));
        m_fileMovie.Close();
        return TRUE;
}
```



START-UP SCREEN

When the program is first loading, the copyright notice is displayed against an image of the magnetization in a thin film media with random anisotropy. The domain image is color coded to indicate the directions of the magnetization in the domains.

This Windows environment contains features that remain constant throughout the operation of the program. The dark area is an OpenGL window, which is the viewing screen for all simulation graphical output. It displays all graphical data as you select them through the LLG Input Sheet and LLG Simulation Sheet Pages; for example, you can display the direction cosines and fields while a simulation is running. This is also the window where movies from previous simulations are displayed. The gray areas to the left are the I/O pages. In this chapter, the functionality of the main window (including graphics) is demonstrated.

Dividing the Graphics Window

The OGL window can be recursively divided into sub-windows for viewing different aspects of the same problem. ***RIGHT CLICK*** on the main window for the following menu. You can either split the window horizontally (resulting in two windows, one above the other), split the window vertically (resulting in two windows side by side) or delete the active window. You cannot delete the last window, as LLG requires that there be at least one active OGL window. You can continue to split the windows and make the nesting and the view sequencing into a configuration of your selection.

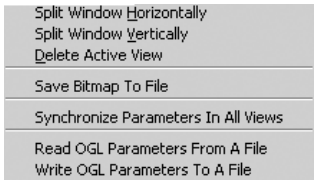

Split Window Horizontally
Split Window Vertically
Delete Active View
Save Bitmap To File
Synchronize Parameters In All Views
Read OGL Parameters From A File
Write OGL Parameters To A File

FIGURE 7. LLG Recursive Window Splitting Menu

Since LLG supports multiple view windows, you can replicate the properties of a single window to all window by selecting the synchonize parameters selection in the menu. In addition, you can read and save OGL parameters to a file for use in later LLG simulations. You can archive the OGL view settings that you prefer so that you can load and run subsequent problems from the same view perspective.

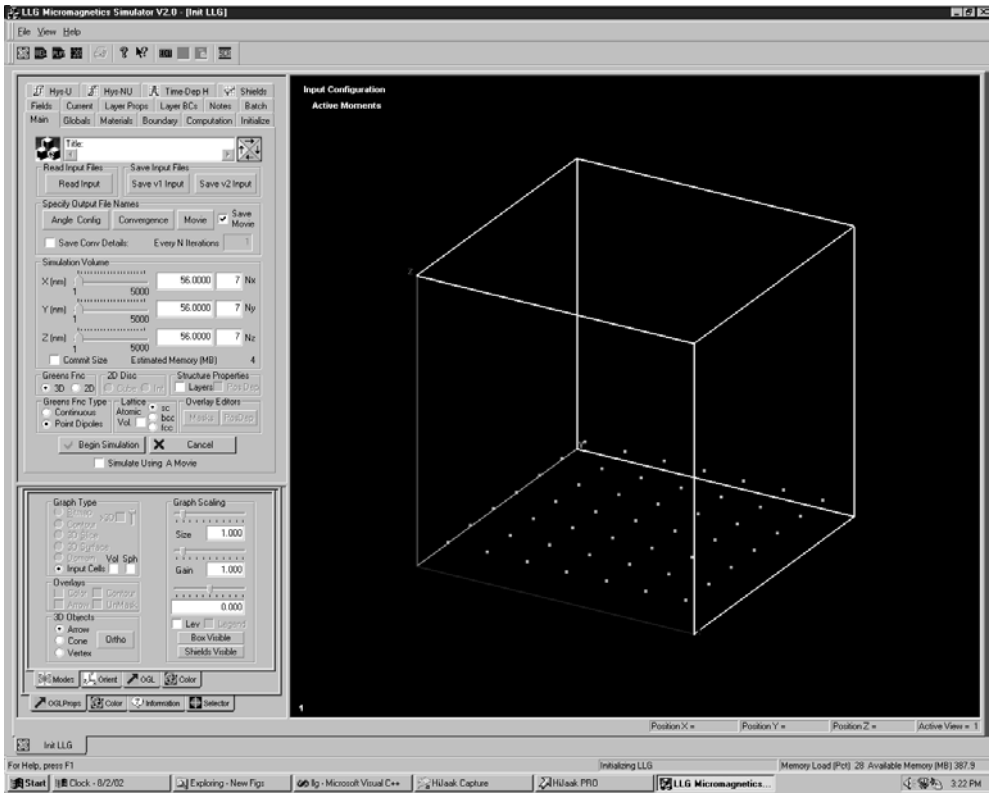


FIGURE 8. LLG Environment

MAIN WINDOW TOOL BAR

FIGURE 9. LLG Main Window Tool Bar

The functions of the tool bar icons, moving from left to right are: (1) New Simulation, (2) View Screen, (3) Movie Screen, (4) 2D Graphics, (5) Print OGL Window, (6) About LLG, (7) Help, (8) Editor, (9) Save OGL Bitmap and (10) Save OGL Bitmap to the Clipboard.

1. The **New** button clears the screen and enables you to start a new simulation. The name of the file in use appears in the window-workbook tab. If you are working with an unnamed file, the program names the files Init LLG, and defaults to these names in the Save function.
2. The **View Screen** button activates the file viewer where you can visualize domain, field and mask files individually.
3. The **Movie Screen** button (see page 195) activates the movie viewer where you can visualize movie files and animation sequences.

4. The **2D Graphics** button enables 2D plotting.

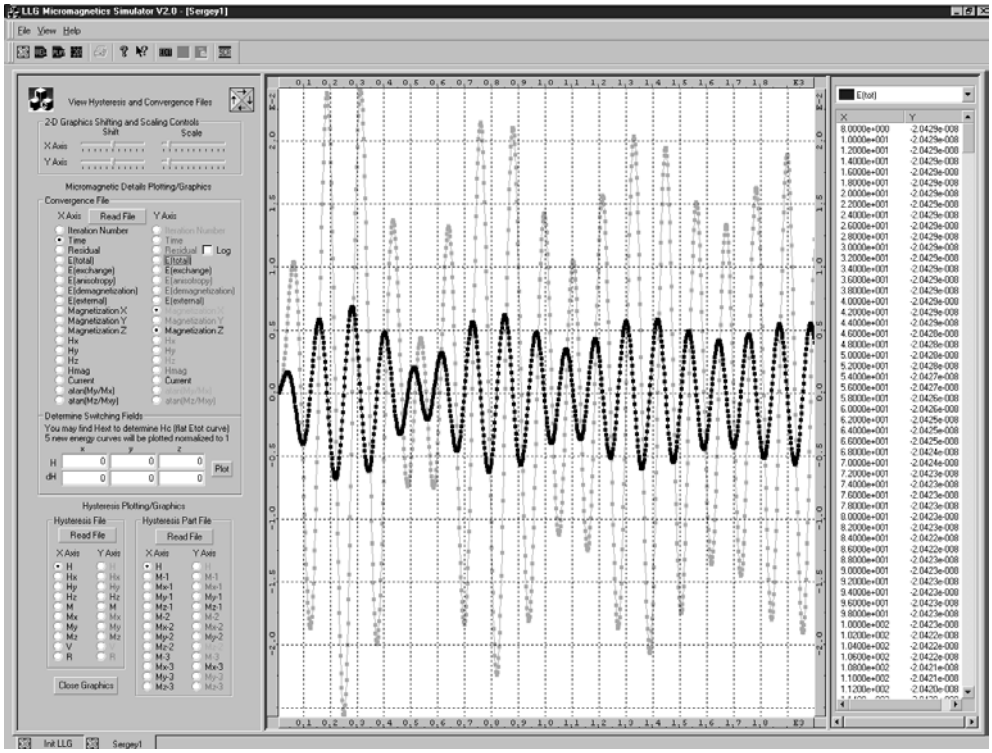


FIGURE 10. 2D Graphics Environment

The 2D Graphics environment is where you can examine the contents of Convergence Files, Hysteresis Files or Hysteresis Part Files. The files can be selectively loaded with the appropriate **Read File** button. The **X-Axis** variable is selected from the list at the upper left; for a given file type, you can select as many **Y-Axis** variables as you want from the list at the upper right. Each x-y pair is a separate plot and can be examined in the window to the right. At the top right, you can scroll through the x-y point pairs in your graph. You may also replot the energy as a function of the externally applied magnetic field in order to more precisely determine the switching field (flat energy curve).
By ***RIGHT CLICKING*** on the graphics window, you have the options to:

- Toggle the Points Window on and off.
- Toggle Autoscale on and off.
- Toggle the Plot Symbols on and off.
- Toggle the Mouse Coordinates tracking on and off.
- Toggle the Grid Overlay on and off.
- Zoom in and out.
- Copy points to the text buffer for pasting into documents.
- Reset the graph Properties.

This is not meant to be the kind of tool that you would find in a commercial graphics software package, but rather is included to allow you to probe your LLG data quickly and efficiently.

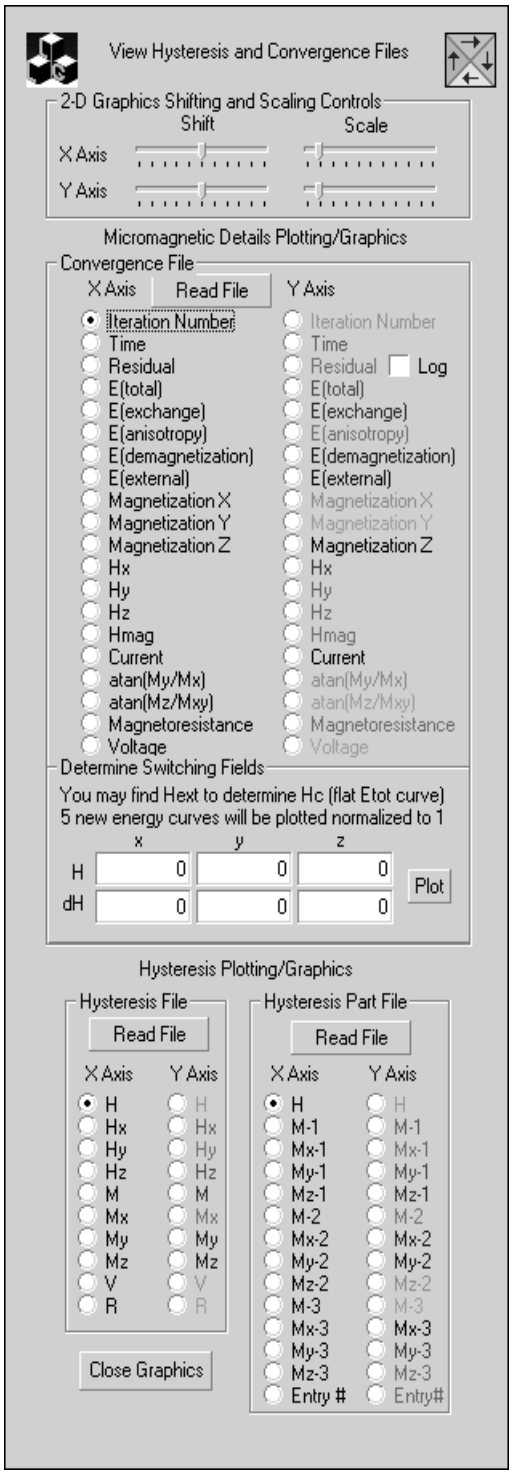


FIGURE 11. 2D Graphics Menu (color coded to match graph colors)

5. The **Print OGL Window** button allows you to print the active OGL window to any Windows supported printer.
6. The **About LLG** button activates the About LLG Dialog Box.

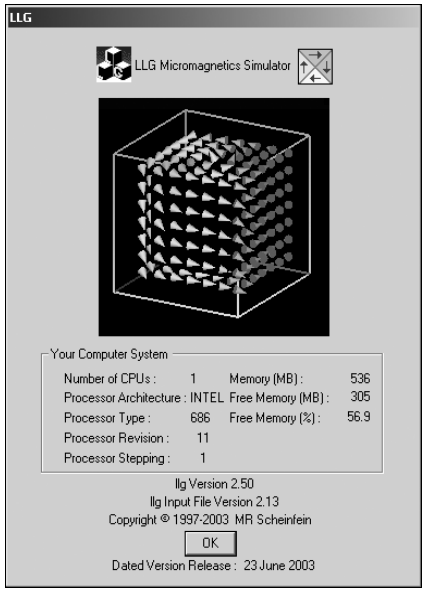


FIGURE 12. About LLG Dialog Box

7. The **Help** button activates help.
8. The **Editor** button activates the LLG File Editor. It has the same functionality as Notepad and WordPad, which you can activate directly from the LLG Editor with the appropriate buttons. The Editor has its own Toolbar.

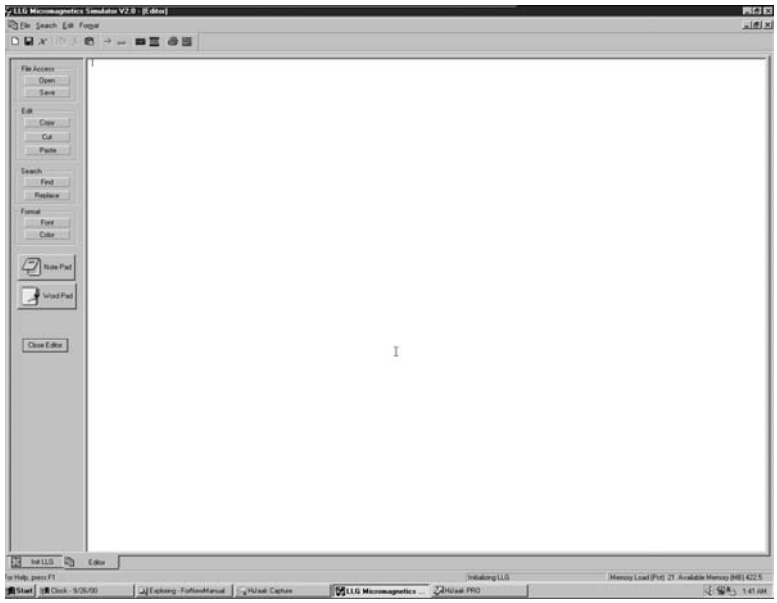


FIGURE 13. LLG File Editor

FIGURE 14. LLG File Editor Toolbar

The functions of the LLG Editor Toolbar icons are, moving from left to right: (1) Open File, (2) Save File, (3) Close Editor, (4) Copy Selection, (5) Cut Selection, (6) Paste Selection, (7) Find, (8) Replace, (9) Change Font of Selection, (10) Change Color of Selection, (11) Print and (12) Print Preview.

9. With the **Save OGL Bitmap** button, you can save your active OGL window to a Windows *.bmp bitmap file.
10. With the **Save OGL Bitmap to Clipboard** button, you can save your active OGL window to a Windows *.bmp bitmap file that is embedded in the Windows clipboard for pasting into another application.

GRAPHICS CONTROLS

LLG implements all of the graphics and utility controls in a single nested property sheet array that is always located in the lower left quadrant of the active desktop. The LLG graphics control is connected to the last activated OGL window. Since the main OGL window can be recursively subdivided, you can click on any subwindow with the mouse to connect that window to the OGL graphics controls. The active window number is indicated in the **Active View Pane** at the lower right in the main window.

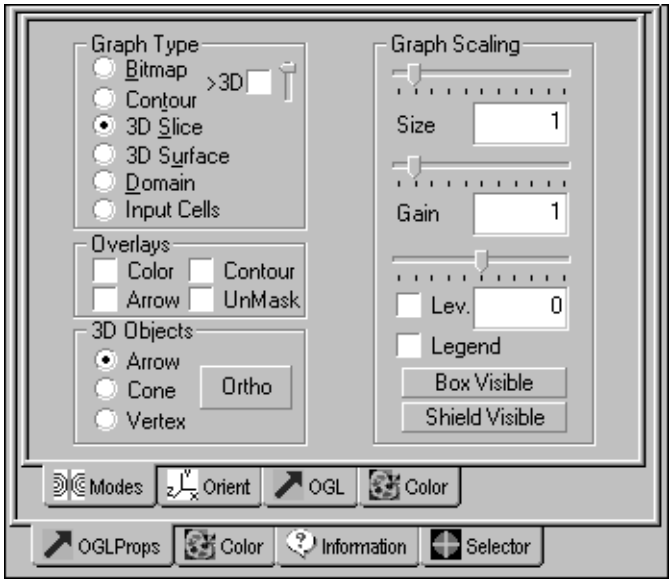


FIGURE 15. LLG Graphics and Utility Control Sheets

Each OGL window is numbered as well. When you click on an OGL window, the properties in the window update the graphics controls. Each window has its own set of OGL properties, and the graphics utilities can be used to modify them. There are four main sheets: (1) OGL Props Sheet, (2) Color Sheet, (3) Information Sheet and the (4) Selector Sheet. Summaries of the functions of each sheet and its pages follow.

OGL PROP SHEET

The OGL Prop Sheet controls all essential OGL functions. There are four sub-pages (1) Modes, (2) Orientation, (3) OGL Properties and (4) Color. You can toggle between the pages by clicking the appropriate (labeled) tab.

OGL PROP SHEET - MODES PAGE

The OGL Modes Prop Sheet-Modes Page is where the display type is set. Several other important OGL features can be set using the Modes Page.

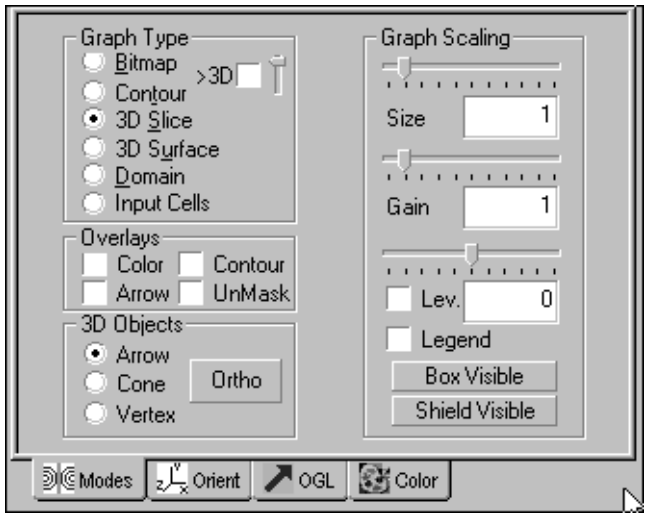


FIGURE 16. OGL Property Sheet - Modes Page

Graph Type

The **Graph Type** allows you to control how the data are viewed, which is key to their interpretation. This is activated after you have completed the Input Phase and started a computation. Scalar (e.g., energy density) or vector (fields and magnetization) data are represented. There are two-dimensional projections (bitmap, contour and domain) and three-dimensional views (slice, surface and input).

- **Bitmap** - The Bitmap Graph Type displays interpolated color pictures of the data on a two-dimensional slice of the structure. For scalar data, such as energy density, the maximum value is by default scaled to red and the minimum value is scaled to blue; all intermediate values are interpolated between these colors. The color index can be altered using the Color Sheet - Table Page. For vector data, such as the magnetization, three panes of bitmap appear, m_x, m_y and m_z (direction cosine) components. Each bitmap has color coded and labeled axes (r, g, b) to orient you. The magnetization direction cosines show m_x (m_y or m_z) = 1 as red, m_x (m_y or m_z) = -1 as blue, and m_x (m_y or m_z) = 0 as black.
- **Contour** - Data are represented in the same fashion as in the Bitmap Graph Type (color) but, instead of a smooth interpolated image, contours of constraint m_x (m_y or m_z) are plotted. By default, red indicates positive increments in (by default) 0.10 values; blue indicates negative increments in -.10 values; in all, by default, there are 20 contours: -.95, -.85…-.05, +.05, +.15…+.85, and +.95. When you image unnormalized variables, such as vector fields, the view is scaled to the minimum and maximum values and coded, as above. The number of contours can be set in the OGL Props Sheet - OGL Page.
- **3D** - This feature allows you to warp the **Bitmap** and **Contour** configurations in 3D. You can adjust the vertical scale gain on the 3D warping with the slide bar adjacent to the 3D check box. The normal 3D angular and position adjustments can be used to center and rotate the view.

- **3D Slice** - You can display the data in either two or three dimensions. The two-dimensional view shows a slice in the selected orientation (X, Y, or Z). An X-slice is a cut along an X-constant plane; with the Slice slide bar or edit box (OGL Props Sheet - Orient Page), you can define the integer constant of the plane's sub-element discretization index for the selected orientation. Therefore, a structure that is defined to be

$$X = 1000\text{ nm} \quad N_x = 100$$
$$Y = 30\text{ nm} \quad N_y = 3$$
$$Z = 500\text{ nm} \quad N_z = 50$$

  has 100 X-slices that display 30 nm x 500 nm Y-Z planes, three Y-slices that display 1000 nm x 500 nm X-Z planes, and 50 Z-slices that display 1000 nm x 30 nm X-Y planes.
- **3D Surface** - This feature is for three-dimensional vector data only, when the surface of the volume is displayed. This view is useful for analyzing three-dimensional structures such as cubes with vortices.
- **Domain** - With this feature, the in-plane components of a vector are projected with a fixed color wheel. Regions of constant magnetization direction, such as in a domain, appear as one color. This is specified in the Color Sheet - Wheel Page.
- **Input Cells** - This shows the input configuration.

Overlays

The **Overlay** configurations are superimposed on the selected **Graph Type.**

- **Color** - You can apply color to regions with position-dependent parameters or layered parameters. You specify the colors themselves on the **Position Dependent Properties Sheet-Params Page** and the **Layer Props Page**. However, these colors appear in the graphics window only when you ***ALSO*** check the **Color Overlay** box in the **Graphics Control**. This can be useful when analyzing complex structures.
- **Arrow** - This control is active for **Domain**, **Bitmap** and **Contour Graph Types** when **3D** warping is ***NOT*** selected. The **Arrow Overlay** superimposes an arrow slice on top of the **Domain**, **Bitmap** and **Contour Graph Types**.
- **Contour** - This control is active for **Domain** and **Bitmap Graph Types** when **3D** warping is ***NOT*** selected. The **Contour Overlay** superimposes a contour map on top of the **Domain** or **Bitmap Graph Type**.
- **Unmask** - This control allows you to visualize computed fields in regions where the magnetization cells have been turned off with the **Mask Editor** (see page 115). When you check the **Unmask Overlay** box, you can visualize the magnetic fields in the holes and in regions where M = 0 that are otherwise not visible.

3D Objects

There are three glyphs for rendering 3-dimensional objects. You can toggle between orthographic and projection 3D visualization.

- **Arrow** - When 3D objects are selected and vector data are present, the arrow is the most graphically ***economical*** representation. It is a line with a carat hat for orientation.
- **Cone** - When 3D objects are selected and vector data are present, the cone is the most graphically ***expensive*** representation. It is a 3D hollow cone whose properties can be set in the OGL Props Sheet - OGL Page.
- **Vertex Cone** - When 3D objects are selected and vector data are present, the vertex cone can be used to provide an alternative representation. The vertex cone is a collection of triangles with aligned tips. The properties of the vertex cone can be set in the OGL Props Sheet - OGL Page.
- **Ortho** - This toggles between orthographic and perspective views of 3D data.

The best **3D Cone** and **Vertex** Cone viewing is with the **OGL Lights** on. It is recommended that you turn the lights off for all other views.

Graph Scaling

- **Box Visible** - This toggles the bounding box.
- **Shield Visible** - This toggles the shields when they are present.
- **Size** - This zooms into and out of the view. You can change the magnification ($0.1 \leq$ magnification ≤ 10) of the view.
- **Gain** - This scales data linearly to amplify sensitivity when you are viewing bitmaps or contours. This is useful for visualizing small changes in data, such as ripple.
- **Lev** - The level indicator can be turned on and off with the **Lev** checkbox. The level indicator is active only in bitmap and contour modes. The level indicator overlays a white contour at the level selected. This tool is useful for demarking individual equidata-value lines (i.e., equimagnetization lines). The value of the contour is displayed in the edit box adjacent to the check box. This adds a quantitative visualization feature to your data analysis.
- **Legend** - This feature allows you to toggle the **Legend** on and off for **Bitmap**, **Contour** and **Domain Graph Types**.

OGL PROP SHEET - ORIENT PAGE

The OGL Modes Prop Sheet-Orient Page is where you translate and rotate the view.

- **X, Y** and **Z** - With this control, you can translate the position of the view. You can shift the center view of the 2D or 3D coordinate system with the X, Y and Z slide bars or edit boxes. The default sets the structure in the center of the window. The units are in nm.
- **Slice** - This allows you to select the slice number to view.
- **Theta** and **Phi** - This allows you to select the view orientation. The angles are defined in the conventional spherical-polar geometry. Theta and Phi are given in degrees.

$$M_x = M_S \sin\theta \cos\phi$$
$$M_y = M_S \sin\theta \sin\phi$$
$$M_z = M_S \cos\theta$$

LLG uses color to establish orientation; the colors of the coordinate axes are:

$\hat{X}$ - Red (r)
$\hat{Y}$ - Green (g) (rgb $\leftrightarrow$ xyz)
$\hat{Z}$ - Blue (b)

- **Slice X, Y, Z** - This allows you to select the 2D projection. For example, selecting X displays the slice where X = constant.

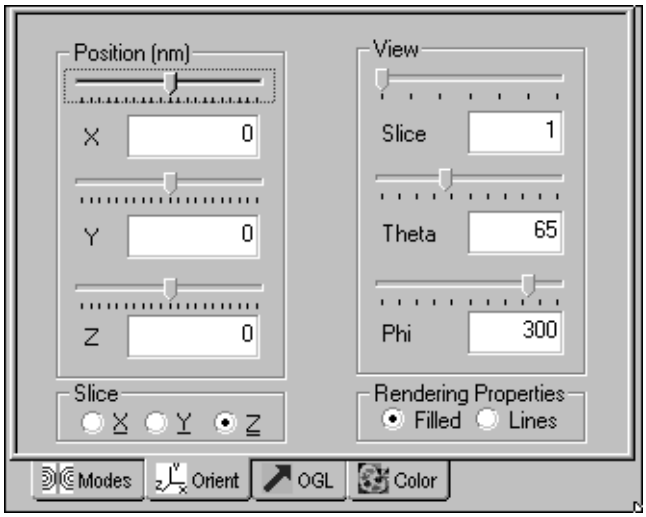


FIGURE 17. OGL Property Sheet - Orient Page

- **Rendering Properties -** You can visualize solid figures, including **Bitmap** and **Domain Graph Types**, with the **Filled** surfaces and out**Lines.**

OGL PROP SHEET - OGL PAGE

The OGL Modes Prop Sheet-OGL Page is where the OpenGL properties can be altered and set directly.

- **Length** - With this you can set the length of the arrow or cone; 0.75 is the default.
- **Radius** - With this you can set the radius of the arrow or cone; 0.25 is the default.
- **Sides** - With this you can set the number of cone sides; 12 is the default. More sides take longer to draw.
- **Arrow Steps** - It is difficult, if not impossible, to see detail when you display all moments for systems that have thousands of sub-elements in each plane. To simplify the view, you can display every other arrow by entering 2 into the Arrow Steps edit box; to display every third arrow, use 3, etc. All of the data remain unchanged. However, an uncluttered view of the vector field simplifies interpretation of order in entire structures.
- **# of Contours** - With this you can set the number of contours; 20 is the default.
- **Size** - With this you can zoom into and out of the view. You can change the magnification ($0.1 \leq$ magnification ≤ 10) of the view. For convenience, this control is on both the OGL and Modes Pages.
- **Gain** - With this you can scale data linearly to amplify sensitivity when viewing bitmaps or contours. This is useful for visualizing small changes in data, such as ripple. For convenience, this control is on both the OGL and Modes Pages.
- **OGL Lights** - With this you can toggle the OGL Lights on and off. The best 3D Cone and Vertex cone viewing is with the lights on. It is recommended that you turn the lights off for all other views.

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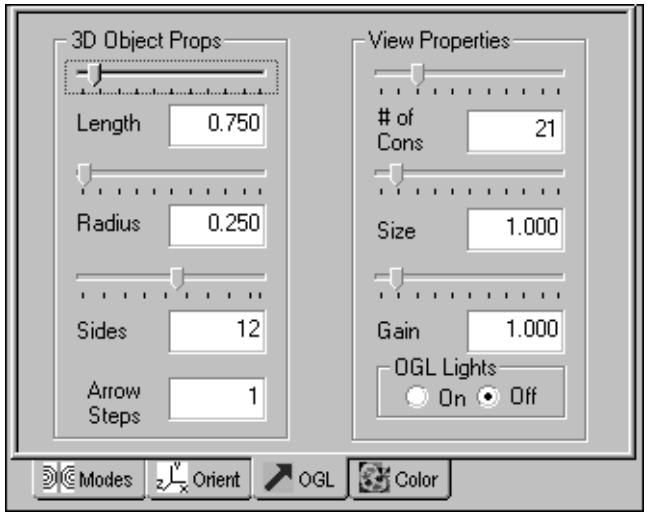


FIGURE 18. OGL Property Sheet - OGL Page

OGL Prop Sheet - Color Page

The OGL Modes Prop Sheet-Color Page is where you set and alter the OpenGL color properties. LLG's view is true 24-bit color.

- You can modify the colors of the foreground and background with the **Red**, **Green** and **Blue** controls, as well as with the **Hue**, **Saturation** and **Brightness** controls, the values of which must be between 0.0 and 1.0.
- To restore the control to the original settings, click the **Revert** button.
- The foreground and background must be changed independently; the **Front: Out, Back: In** button allows you to toggle between modifying foreground and background colors.
- The program defaults to the foreground view. For saving LLG bitmaps for eventual printing on a standard rather than a color printer, click the **B/W** button.

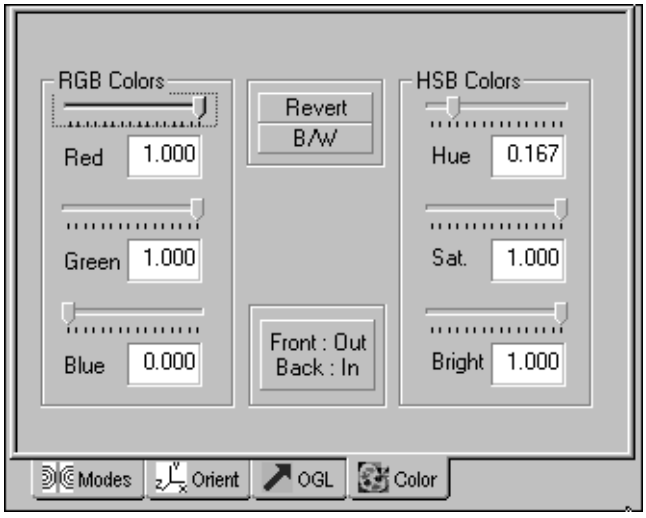


FIGURE 19. OGL Property Sheet - Color Page

OGL COLOR SHEET

The OGL Color Sheet controls all essential OGL color functions. There are three sub-pages: (1) Color, (2) Wheel and (3) Table. You can toggle between the pages by clicking the appropriate tab.

OGL COLOR SHEET - COLOR PAGE

The OGL Modes Prop Sheet - Color Page is where you can alter and set the OpenGL color properties directly. LLG's view is true 24-bit color. You can modify the colors of the foreground and background with the **Red**, **Green** and **Blue** controls, as well as with the **Hue**, **Saturation** and **Brightness** controls, the values of which must be between 0.0 and 1.0.

This page has identical functionality to that of the OGL Props Sheet - Color Page, except for the additional control of the drop-down color button where colors can be selected directly from the Windows color palette. The active selected color is displayed in the color box at the bottom of the page.

.

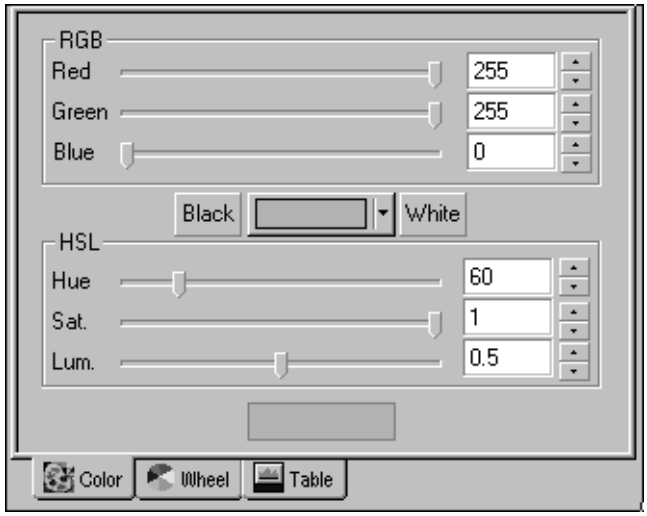


FIGURE 20. OGL Color Sheet - Color Page

OGL Color Sheet - Wheel Page

The OGL Color Sheet-Wheel Page is where you can alter and set the OpenGL color wheel properties directly. Color wheels are used to display **Domain Graph Type**. The principle is to select colors over in-plane angular ranges that are indicative of domain orientations. To provide the flexibility to capture this functionality, the Color Wheel can be decomposed into as many as six regions (that is, six-fold symmetry or anisotropy), where each range of angles can be specified independently.

The Color Wheel allows you to select separately the number of active regions (**Angle 1** through **Angle 5** check boxes), the angle to start (end) that region (center) and the color to interpolate to at that angle. The colors are selected by clicking the appropriate color box (**Color 1** through **Color 5**).

1. Check an **Angle** box.

1. Click a **Color** box, which redirects you to the **OGL Color Sheet-Color Page**, just described.
2. Select a color from the **Color Page**.
3. Click the **Wheel** tab to return to the **Color Wheel Page**. The selected color is automatically loaded into the **Color** box for the selected angle.

The **Color Wheel** itself at bottom left can be rotated with the slider, the thumb-wheel or the edit box. Once you find your favorite Color Wheel selections, save them for future use. Color wheel files can be **Save**d or **Load**ed by clicking the appropriate button.

You must click the **Apply** or **Reset** button to activate a new Color Wheel for the actively selected OGL view.

Please note that ***the angular range must be monotonically increasing***, i.e. Angle 5 > Angle 4 > Angle 3 > Angle 2 > Angle 1.

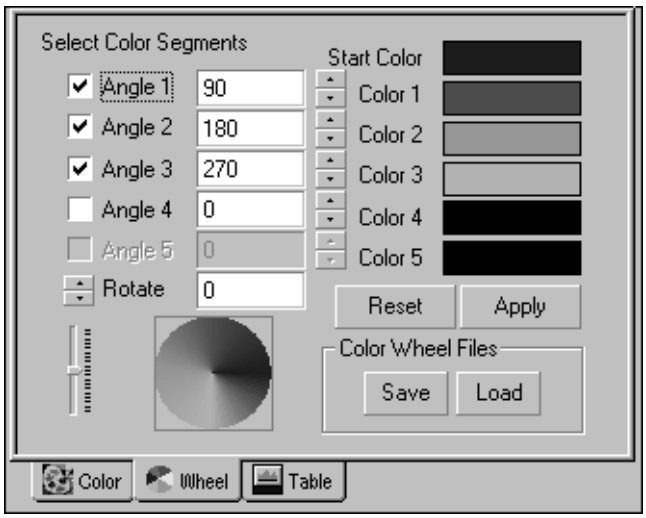


FIGURE 21. OGL Color Sheet - Wheel Page

OGL COLOR SHEET - TABLE PAGE

The OGL Modes Prop Sheet-Table Page is where you can alter and set the OpenGL color table properties directly. Color tables are used to display **Bitmap** and **Contour Graph Types**. The principle behind using a color table is to select colors over in-plane angular ranges that are indicative of domain orientations. The color table can be decomposed into as many as five regions, where each range can be specified independently.

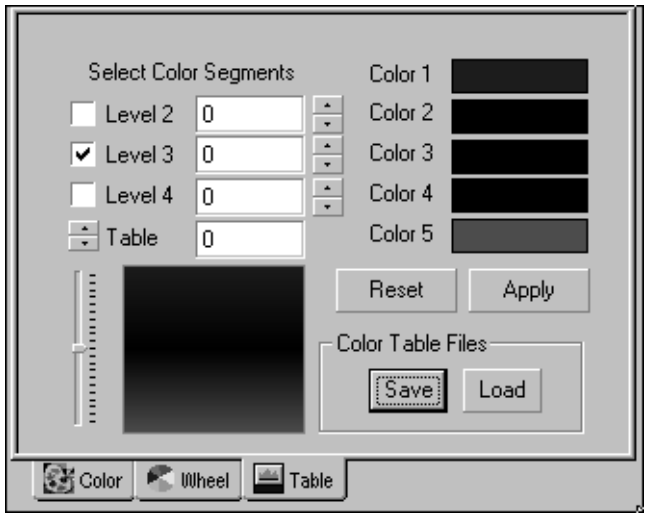


FIGURE 22. OGL Color Sheet - Table Page

The **Color Table** allows you to select separately the number of active regions (**Level 2** through **Level 4**), the angle to start (end) that region (center) and the color (**Color 1** through **Color 5**) to interpolate to at that direction cosine.

1. Check a **Level** box.
2. Click a **Color** box, which redirects you to the **OGL Color Sheet-Color Page**, just described.
3. Select a color from the **Color Page**.
4. Click the **Table** tab to return to the **Color Wheel Table**. The selected color is automatically loaded into the **Color** box for the selected **Level**.

The color table itself can be shifted with the slider at the bottom left. Once you find your favorite color table selections, save them for future use.

Color table files can be **Save**d or **Load**ed by clicking the appropriate button. You must click the **Apply** (or **Reset**) button to activate a new color table for the actively selected OGL view

Please note that ***the direction cosine range must be monotonically increasing***, i.e. 1.0 > Level 2 > Level 3 > Level 4 > Level 5 > -1.0.

OGL Information Sheet

The OGL Information Sheet provides utilities and information about your system. These features are provided for convenience and offer no extra features beyond those of Windows NT. There are five sub-pages: (1) Info, (2) Disks, (3) Output, (4) Clock and (5) Calculator. You can toggle between the pages by clicking the appropriate tab.

OGL Information Sheet - Info Page

Through the OGL Information Sheet-Info Page, you can examine system information.

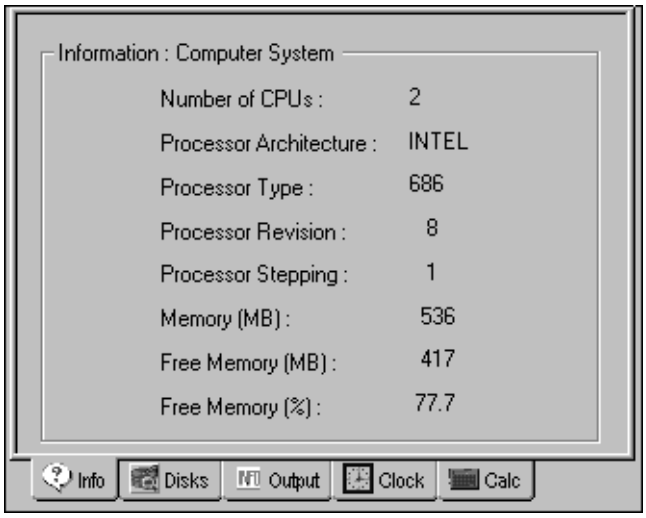


FIGURE 23. OGL Information Sheet - Info Page

OGL Information Sheet - Disks Page

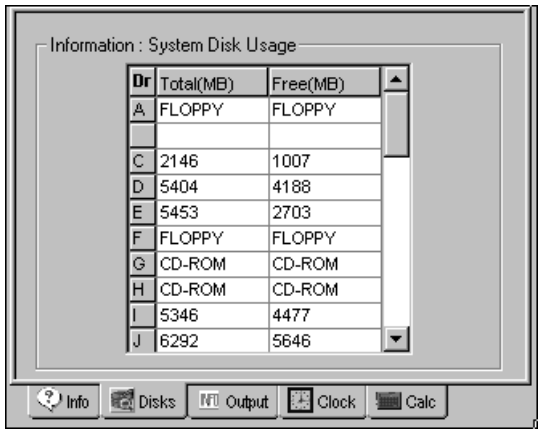


FIGURE 24. OGL Information Sheet - Disks Page

Through the OGL Information Sheet-Disks Page, you can examine disk space.

OGL Information Sheet - Output Page

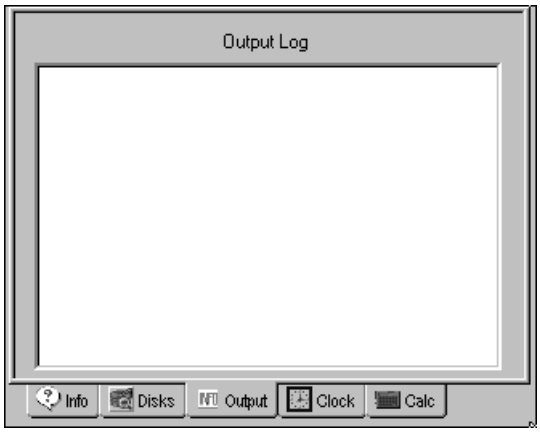


FIGURE 25. OGL Information Sheet - Output Page

The OGL Information Sheet-Output Page is where messages are written for the user when LLG performs some special task.

OGL Information Sheet - Clock Page

FIGURE 26. OGL Information Sheet - Clock Page

The OGL Information Sheet - Clock Page provides you with a clock and a calendar.

OGL Information Sheet - Calculator Page

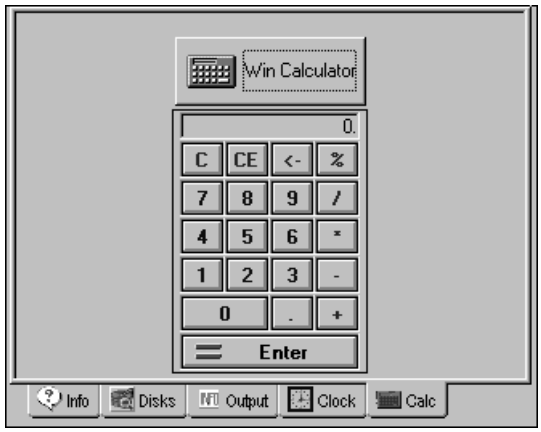


FIGURE 27. OGL Information Sheet - Calc Page

The OGL Information Sheet - Calc Page provides you with a calculator.

OGL Information Sheet - Demag Field Calculator

The OGL Information Sheet - Demag Page provides you with a demagnetization field calculator for uniformly magne-

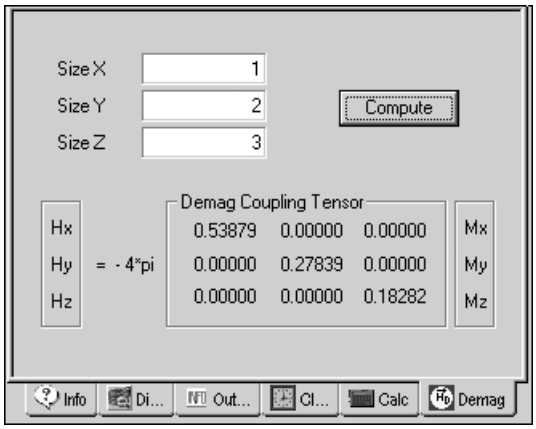


FIGURE 28. OGL Information Sheet - Demag Page

tized structures bounded by cartesian planes.

OGL Selector Sheet

The OGL Selector Sheet allows you to probe the properties of the OGL window. You can access all array values (such as magnetization and field) and parameters (such as magnetization and position). There are three sub-pages: Main, Arrays and Properties. You can toggle between the pages by clicking the appropriate tab.

To activate the selector (picker), check the **Activate Picker** box at the upper right. When you position the cursor over an OGL window, the arrow cursor changes to a target cursor. You can select objects only in **3D Slice Graph Type** using Arrow, Cones or Vertex Cones. To select an object, position the cursor over the object you wish to extract properties from and click. When you click an object, its properties are loaded into all three Selector Pages.

You ***MUST*** check the **Activate Picker** box before ***EACH*** selection. This allows you to toggle between selector and normal interaction with your views.

OGL Selector Sheet - Main Page

Through the OGL Selector Sheet - Main Page, you can examine position and direction cosine information.

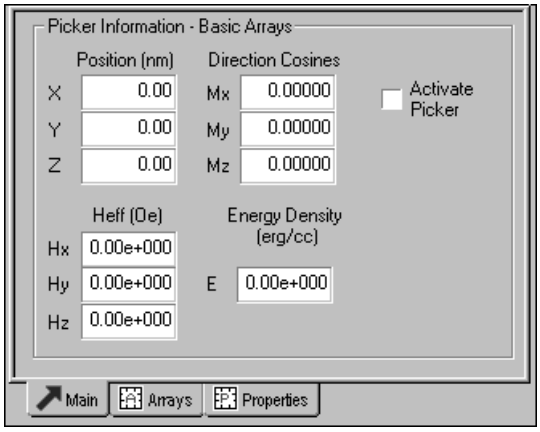


FIGURE 29. OGL Selector Sheet - Main Page

OGL Selector Sheet - Arrays and Properties Pages

Through the OGL Selector Sheet-Arrays/Properties Page, you can examine all array/property information.

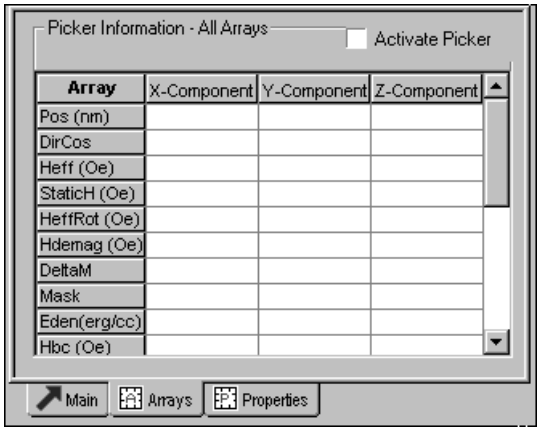


FIGURE 30. OGL Selector Sheet - Arrays Page

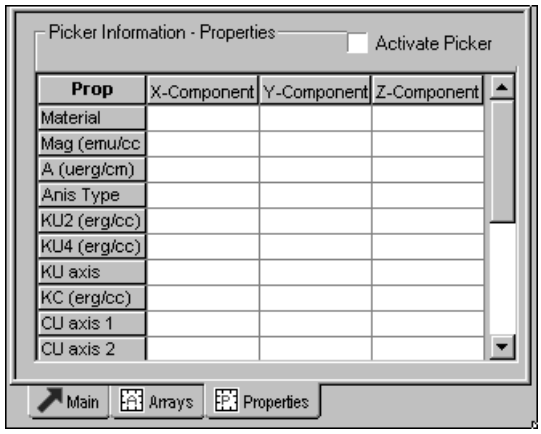


FIGURE 31. OGL Selector Sheet - Properties Page

MEMORY LOAD AND MEMORY STATUS PANE

Refer to the window toward the bottom center of the screen for the memory load and the available physical memory. LLG does not modify Windows NT memory in the sense that, if an unusually large disk cache is allocated in physical memory, then the program assumes that this memory is in use and does not try to reallocate it. If you have less memory than anticipated, close all other programs. Since the program uses a lot of CPU cycles, it is generally best not to run other programs while you run LLG.

PROGRAM STATUS PANE

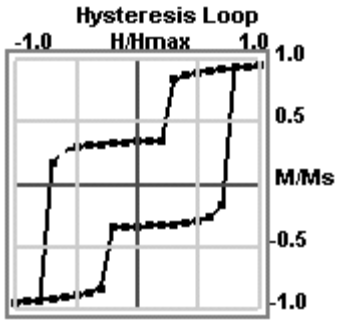
Consult the window toward the bottom right of the screen for the status of program operations. For instance, while the program is starting up and while the LLG Input Sheet is in view, the window says “Initiating LLG Micromagnetics.” Likewise, if you select the **Pause** button during a computation, it reads “Pausing Computation.”

LLG UTILITIES: ALTERING LLG’S APPEARANCE AND BEHAVIOR

LLG uses two utilities to alter the look, feel and functionality of the program. Close all LLG windows using the menu selection located under File at top left. The main menu will be replaced with the utility menu. Under Tools, you will find the following:

FIGURE 32. Utility tools.

LLG’s flat look and feel can be toggled on/off by checking the Install Cool Tools menu selection. LLG uses a numerical filter to guarantee that edit fields are input as numbers. If you rapidly enter a multidigit number, LLG will only take the first digit. You can now toggle the numerical filtering tool on/off. Some users consider this feature to be a bug. However, it prevents LLG from having to error trap every data entry to check type. If you opt to turn the numerical filter off, you will be responsible for insuring that the data as entered are numbers rather than arbitrary character strings.



INPUT SEQUENCE

Once you have initiated a simulation by clicking the **New** (Domain) button, the **Input Data Sheet** appears. This sheet and its pages are where you specify the data during the Input Phase. This section of the Manual outlines each page and its options, which are best completed in the order in which they are presented. The general strategy is to enter parameters in the following order: (1) global, (2) boundary conditions, (3) computational, (4) initialization, (5) static and pinning fields, (6) notes, (7) hysteresis loops, time-dependent fields or shielded media fields, (8) layer, (9) layer boundary conditions, (10) position-dependent, (11) and currents. If you use 2D currents only, you might specify them after entering the static and pinning fields. The strategy below indicates how LLG actually manipulates data internally.

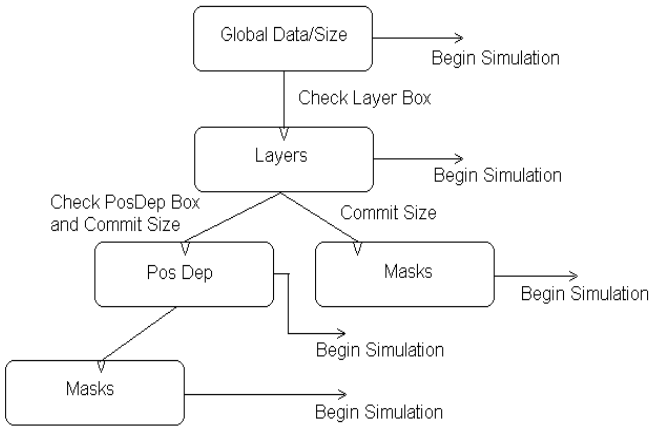


FIGURE 33. Input Data Strategy

When LLG initializes its parameter arrays and allocates memory, first it fills in the layer parameters with globally specified parameters and then it fills in the layer-specific properties. Once layers have been created, if position-dependent parameters are required, LLG uses the layers properties to initialize the position-dependent parameters. This allow you to create a problem with layered properties and to make only one parameter position-dependent.

IMPORTANT NOTE:

In v2 of LLG, you ***MUST*** check the **Layers** box under **Structure Properties *BEFORE*** you input layered or position-dependent parameters. Checking the **Layers** box gives you access to the **Layer Props Page**.

When you apply position-dependent parameters to a 1-layer structure, you ***MUST*** specify it as 1-layer on the **Layer Props Page**. In this case, the layer thickness (defined on Layer Props Page) and the thickness of the structure (defined on Main Page) are equal. After you have input layered properties, the **PosDep** box under **Structure Properties** is enabled, allowing you to configure a position-dependent problem.

Checking the **Commit Size** box on the Main Page allocates memory for the arrays that represent your structure and fixes the discretization volume. You ***MUST*** check the **Commit Size** box ***BEFORE*** you input or edit **Masks** (Chapter 21) or alter parameters with the **Position Dependent Parameter Editor** (Chapter 22)**.** Once memory has been allocated, you cannot change the number of cells in the problem. If you need to alter the problem's size, you must reinitialize LLG.

INPUT SEQUENCES FOR MASK, LAYER AND POSITION-DEPENDENT DATA

For Global and Mask Data

1. Enter Global data.
2. If using Masks, check the **Commit Size** box on the Main Page.
3. Click the **Masks** button on the Main Page.
4. Enter or load the mask through the **Mask Editor**.

Note: If your structure is a single material layer*, DO NOT* check anything under Structure Properties on the Main Page.

For Global, Layer and Mask Data

1. Enter Global data.
2. Check the **Layers** box under Structure Properties on the Main Page.
3. Enter data for each layer through the **Layer Props Page**.
4. Click the **Masks** button on the Main Page.
5. Enter or load the mask through the **Mask Editor**.

For Global, Layer, Position-Dependent and Mask Data

1. Enter Global data.

   Check the **Layers** box under Structure Properties on the Main Page.
2. Enter layer data on the **Layer Props Page**.
3. Check the **PosDep** box (not the button) under Structure Properties on the Main Page.
4. Check the **Commit Size** box on the Main Page.
5. Click the **PosDep** button on the Main Page.
6. Enter data with the **Position Dependent Data Editor**.
7. Click the **Masks** button on the Main Page.
8. Enter or load the mask through the **Mask Editor**.

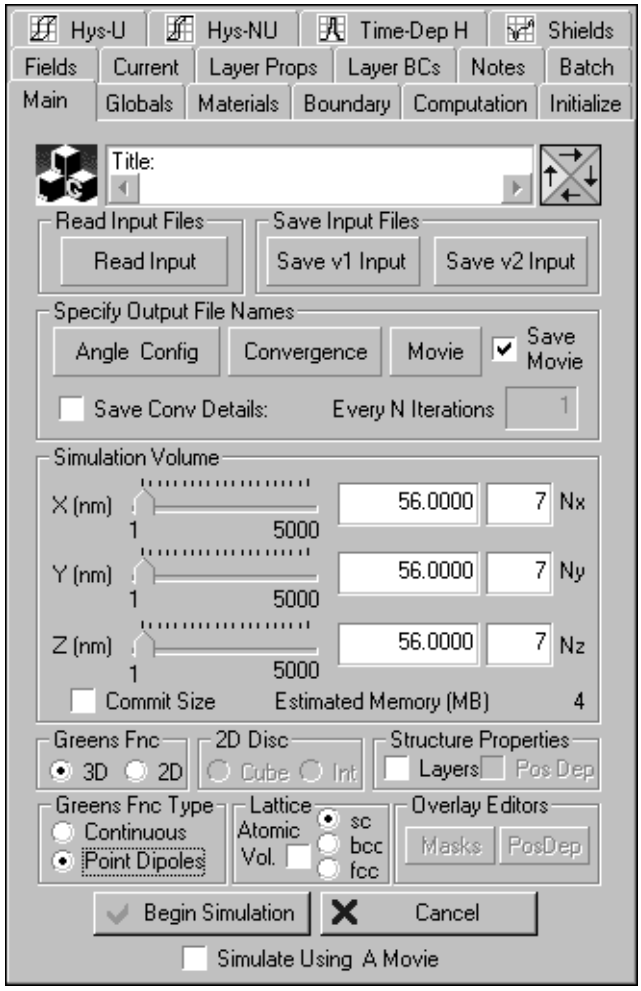


FIGURE 34. Input Data Sheet - Main Page

VARIABLE	LIMITS
X (nm)	$0.01 < X < 10^6$
Y (nm)	$0.01 < Y < 10^6$
Z (nm)	$0.01 < Z < 10^6$
N_x (number in X)	$1 < N_x < 10^6$
N_y (number in Y)	$1 < N_y < 10^6$
N_z (number in Z)	$1 < N_z < 10^6$

Clicking Accept Changes for Your Input to Take Effect

EXCEPT for the **Main Page**, you ***MUST*** click the **Accept Changes** button on each input page for your changes to take effect. Since all of the Input Pages exist concurrently, LLG needs some way of knowing that you intend the changes to be made to the LLG data. Data I/O in the Man Input Page is used to specify input data files and output data files.

SAVING DATA I/O FILES

When you load (save) the input parameter file (when you complete data specification), all output files are automatically created with the root name and appropriate file suffixes. When you do not save or load the input files, you are prompted by LLG for the required file names. It is always desirable to save the input data files with new file names prior to starting a new computation. The parameter files contain a complete ASCII representation of ALL input data. Refer to Chapter 4 on Loading/Saving *.llg Files for information on reading input and saving output files.

- Read Input Files: Read Input — Specify *.llg_param file for input.
- Save Input Files: Save v1 Input — Specify *.llg_param file for output-v1 file. (Disabled in v2.50+)
- Save Input Files: Save v2 Input — Specify *.llg_param file for output-v2 file.
- Specify Output File Names: Angle Config — Specify *.llg_dom file for output.
- Specify Output File Names: Convergence — Specify *.llg_conv file for output.
- Specify Output File Names: Movie — Specify *.llg_movie file for output.
- Specify Output File Names: Save Conv Details — Save detail to the convergence file selector.
- Specify Output File Names: Every N-Iterations — Save conv detail every n-iterations specifier.
- Specify Output File Names: Save Movie — Save movie file selector.

SAVING CONVERGENCE DATA

To save the transient energies and magnetizations to file, check the **Save Conv Details:** box, which enables the **Every N Iterations** edit field. Then, enter into the edit field how often you want the data saved to file. For example, if you enter 1, LLG writes the energies at every iteration; if you enter 10, LLG writes to the file every 10 iterations. You can use the **2D Graphics** tool (see page 55) to view these files interactively as they are written.

GREEN'S FUNCTION

LLG is a full two- and three-dimensional micromagnetics calculator. The difference between these two computation engines is in the structure of the Free Space Green's Function for the computation of the magnetostatic self-fields. Most simulations will employ the 3D Green's Function. However, you should select the 2D Green's Function for simulating domain walls that have 2D symmetry. Several options are specific to the 2D calculation engine, including the interface discretization schemes. The Green's Function for the problem ***CANNOT*** be changed once a simulation has begun.

IMPORTANT NOTE:

All **2D** Green's Function problems require cubic (rods) cells. The discretization ***CANNOT*** be modified once the input is complete.

GREEN'S FUNCTION TYPE

For 3D simulations, you can use either a continuous magnetostatic hamiltonian (**Cont**), which is recommended, or a point-dipole approximation (**Pt Dipole**). This affords you extra flexibility in seeing the real deviations from the simple point-dipole approximation in determining the minimum energy configuration. Although you will most likely never choose to use point dipoles, such a model is useful when comparing analytic results and computations in critical phenomenon theory. Currently, point-dipole fields are used only in 3D computations. This selection ***CANNOT*** be changed once a simulation has begun.

2D Discretization

For 2D problems, continuous boundary conditions can be selected in the **Boundary Page**. To this end, a separate discretization scheme has been implemented, whereby the self-fields are computed interface by interface rather than cell by cell. This option will be of little or no interest unless you wish to simulate the central portion of a continuous film or the top of a semi-infinite substrate. (**NOTE**: This feature is presently not fully implemented in v2, which is the same as in v1.)

Simulation Volume

The **Simulation Volume** is the discretized system under study. Please take care when entering the discretization volume. A uniform cubic discretization scheme has no intrinsic demagnetization effects within each sub-element. Non-uniform grids have non-uniform demagnetization fields within the cell. The variable cell size has been implemented for computing thin film properties, where out-of-plane magnetization components are rare. In this case, thin platelet discretized elements can be selected, but they should be square in-plane to prevent a magnetic field self-bias. Uniform grids will always produce unbiased solutions. To specify a problem, enter the dimensions (nm) using the sidebars or edit boxes. Since the discretization is uniform rectangular, the dimensions must be integral multiples of some minimum cell dimension along that direction. The memory required to compute a given structure is shown; LLG will not let you exceed the physical memory capacity of the computer.

Simulate a Movie

Once you have completed a simulation and stored a movie, you can reinitiate the calculation, whereby, instead of recomputing the magnetization, you can sequentially load the direction cosines that are stored in the movie file into the simulation.

In this mode, you can replay a movie and simultaneously visualize the effective fields and energies associated with the direction cosines stored in the movie. The limiting factor is the availability of enough memory, since all computational arrays are allocated and the entire movie file is loaded. This mode allows you to examine all of the simulation details after you have completed a simulation. The Simulate a Movie options are described in Chapter 23-Simulation.

To use this option, you must check the **Simulate a Movie** box before beginning a simulation.

Atomic Computations

LLG can be utilized to run computations on atomic lattices. In general, LLG operates on a simple cubic lattice. In this mode. the magnetizations can be treated as continuous variables, or discrete dipoles. To use an atomic lattice computation you must first check the point dipole approximation. Now check the Vol checkbox to activate the atomic volume selection and check the radio button with the lattice as (sc) simple cubic, (bcc) body centered cubic, or (fcc) face centered cubic. Once you commit the memory, LLG will display the cells, as shown below on a 3x3x3 lattice. Please note that LLG will remove atoms from the designated simple lattice to form bcc or fcc lattices so appropriate cell sizes must be selected. Also, the exchange calculator will now include all nearest neighbors in the exchange energy computation.

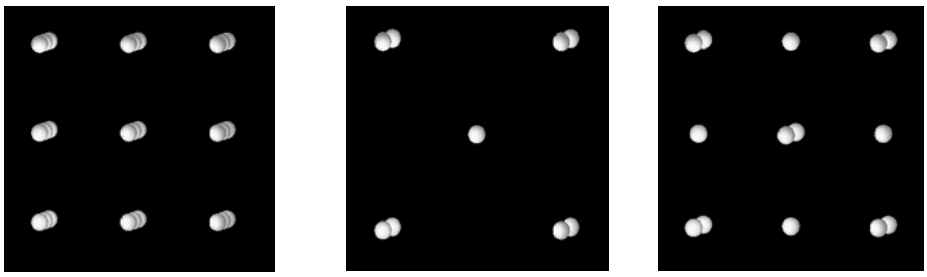
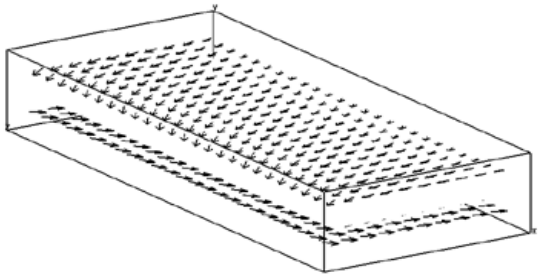


FIGURE 35. SC, BCC and FCC Lattices on 3x3x3 Sites Viewed 1^o off the x-y Plane and 3^o off the y-z Face

CHAPTER 7

Inputting Data into LLG-Globals



Global LLG parameters are those that are specified for every cell in the **Simulation Volume**. The **Input Data Sheet-Globals Page** is shown on the following page. The parameters are summarized below.

DESCRIPTION	VARIABLE	LIMITS
Saturation Magnetization	M_s (emu/cm^3)	$0.0 < M_s \leq 10^6$
O(2) Uniaxial Anisotropy	K_{u2} (erg/cm^3)	$-10^{10} \leq K_{u2} \leq 10^{10}$
O(4) Uniaxial Anisotropy	K_{u4} (erg/cm^3)	$-10^{10} \leq K_{u4} \leq 10^{10}$
Cubic Anisotropy	K_c (erg/cm^3)	$-10^{10} \leq K_c \leq 10^{10}$
Exchange Stiffness	A (μerg/cm)	$-10^2 \leq A \leq 10^2$
Surface Anisotropy	K_s (erg/cm^2)	$-10^{10} \leq K_s \leq 10^{10}$
Resistivity	ρ (μohm/cm)	$0.01 \leq \rho \leq 10^6$
Anis. Magnetoresistance	AMR (%)	$0.0 \leq AMR \leq 1.0$
Anisotropy Type	KType	U, C or Both
Easy Axis Direction	KDir	X, Y, Z or Any
Easy Axis Direction Cosines	$A_{x, y, z}$	$0.0 \leq A_{x, y, z} \leq 1.0$

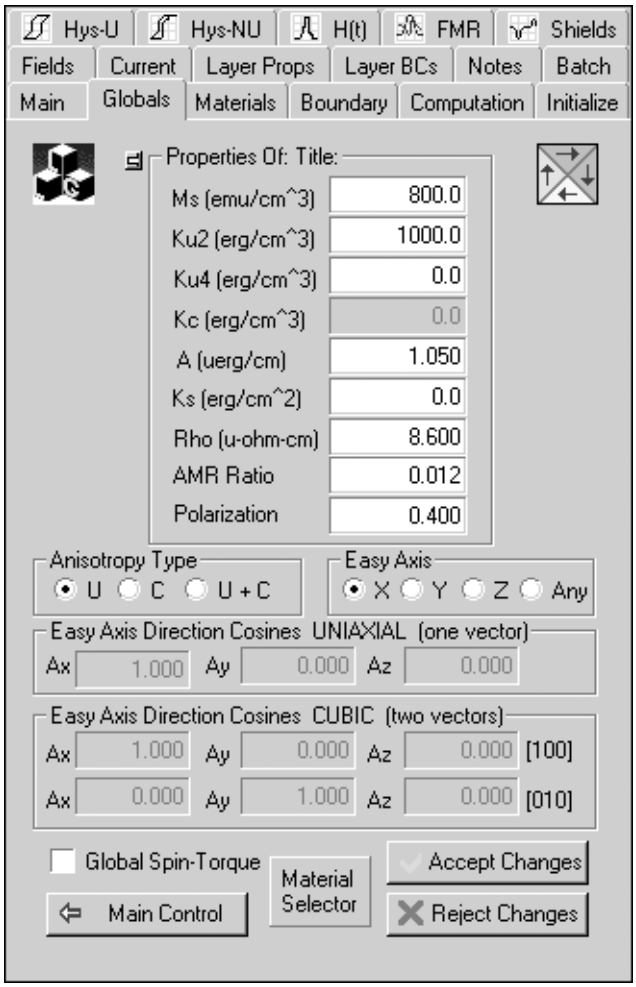


FIGURE 36. Input Data Sheet - Globals Page

USING THE MATERIALS DATABASE TO SELECT PARAMETERS

There are two methods for using the Materials Database for entering parameters.

INPUT SEQUENCES FOR MATERIALS DATABASE

Recommended Path: Globals Tab/Material Selector	*Materials Tab*
1. Click the **Globals** tab. 2. Click the **Material Selector** button to access the Materials Database to select parameters. 3. ***Enter*** your data (see the next chapter on Materials). 4. Click the **Accept** button, which returns you to the **Globals Page**. 5. Enter data into the **Globals Page**; if you wish, click the arrow to the left of "**Properties Of**" to enter a title for your material. 6. Click **Accept Changes,** which returns you to the **Main Page**.	1. Click the **Material** tab to access the Materials Database to select parameters. 2. ***Enter*** your data (see the next chapter on Materials). 3. Click the **Accept** button, which returns you to the **Main Page**. 4. Click the **Globals** tab. 5. Enter data into the **Globals Page**;If you wish, click the arrow to the left of "**Properties Of**" to enter a title for your material. 6. Click **Accept Changes,** which returns you to the **Main Page**.

With the recommended sequence on the left in the table above, you are less likely to make the error of exiting the parameter setup without accepting your Global Parameter input, because you are automatically returned to that Page (step 4, left) instead of the Main Page (step 3, right) after using the Materials Database.

Once you have entered data into the **Globals Page**, you ***MUST*** click the **Accept Changes** button for your changes to update the LLG data structures. If you do not, you will lose your changes when you leave this property page. At any time, you can click the **Main Control** button to return to the **Main Page,** but remember to **Accept Changes** before exiting if you want your changes to take effect.

CONVENTION FOR ANISOTROPY

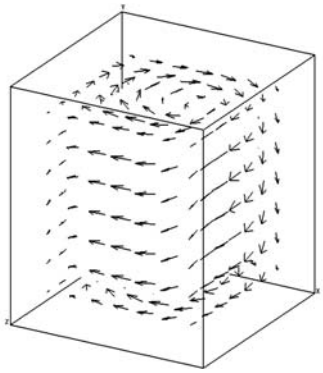
When the anisotropy coefficients are positive, the internal energy due to anisotropy will always be positive. The Uniaxial energy density is written as $E_u=K_{u2}(1-(\underline{m}.\underline{\alpha})^2) + K_{u4}(1-(\underline{m}.\underline{\alpha})^4)$, where $\underline{\alpha}$ is a unit vector along the easy direction. The surface anisotropy is taken as $E_s=1/2K_s(\underline{m}.\underline{n})^2$ where $\underline{n}$ is the outward facing unit normal vector. Thus positive K_s has the effect of forcing moments back into the surface in this convention. The interface anisotropy in the Layer Page has the similar form $E_i =1/2K_i(\underline{m}.\underline{m})$. The interface effective field is simply $-K_i\underline{m}$, which favors out-of-plane magnetization when $K < 0$. This is the convention in LLG.

GLOBAL SPIN TORQUES

Facilities to compute spin-torque in non-layered systems has been added in v2.50 (see Currents Chapter). Whenever there is a divergence of M in the presence of current, there is the possibility to exchange angular momentum (i.e. like in the layered case) between non-aligned spin-moments. Layered system spin torques (Current Page) and Global spin-torques cannot be used at the same time. Since this feature is experimental, this parameter in not saved in the parameter file, hence you will need to check it each time you want to use it.

CHAPTER 8

Inputting Data into LLG-Materials



LLG material parameters can be saved and loaded into a database. The **Input Data Sheet-Materials Page** is shown on the following page. The parameters are summarized below.

DESCRIPTION	VARIABLE	LIMITS
Saturation Magnetization	M_s (emu/cm^3)	$0.0 < M_s \leq 10^6$
O(2) Uniaxial Anisotropy	K_{u2} (erg/cm^3)	$-10^{10} \leq K_{u2} \leq 10^{10}$
O(4) Uniaxial Anisotropy	K_{u4} (erg/cm^3)	$-10^{10} \leq K_{u4} \leq 10^{10}$
Cubic Anisotropy	K_c (erg/cm^3)	$-10^{10} \leq K_c \leq 10^{10}$
Exchange Stiffness	A (μerg/cm)	$-10^2 \leq A \leq 10^2$
Surface Anisotropy	Ks (erg/cm^2)	$-10^{10} \leq K_s \leq 10^{10}$
Resistivity	ρ (μohm/cm)	$0.01 \leq \rho \leq 10^6$
Anis. Magnetoresistance	AMR (%)	$0.0 \leq AMR \leq 1.0$
Anisotropy Type	KType	U, C or Both
Easy Axis Direction	KDir	X, Y, Z or Any
Easy Axis Direction Cosines	$A_{x,y,z}$	$0.0 \leq A_{x,y,z} \leq 1.0$

From the **Materials Page**, you can load the pre-coded properties of Fe, Co, Permalloy and vacuum into the appropriate edit fields. Once you have selected a material, its name appears in the **Global Page** following "**Properties Of**."

CREATING A MATERIALS DATABASE

You can use the **Materials Page** for saving material properties that you have input yourself. To create a database:

1. Enter the material's property values and the name of the material in the edit boxes.
2. Click the **Load into Data List** button to register the material in the drop-down menu.
3. To store the database to a file for permanent archival, click the **Save Database** button and name the file.

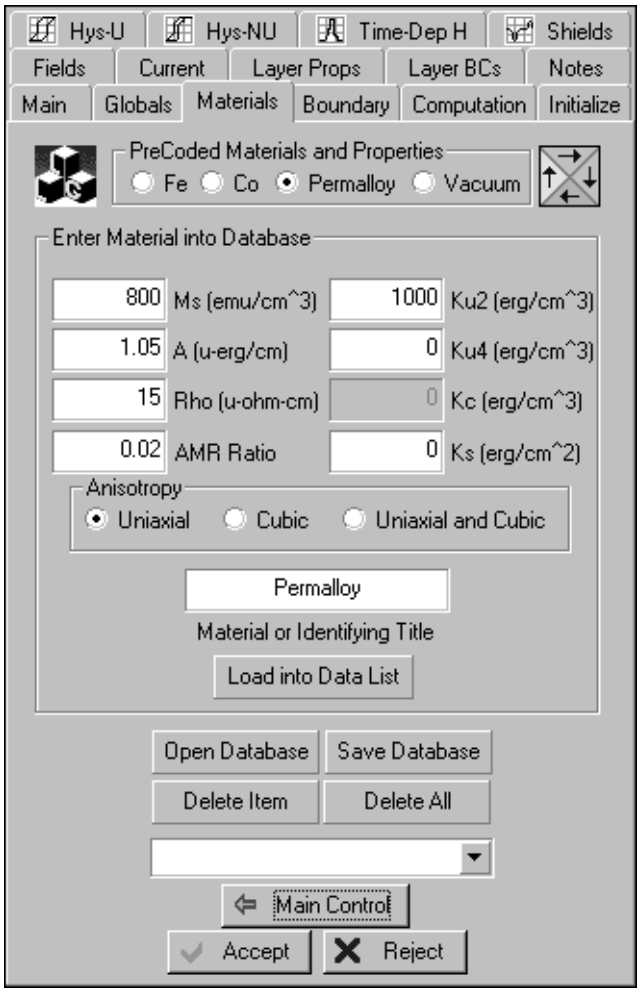


FIGURE 37. Input Data Sheet - Materials Page

LOADING A PREVIOUSLY SAVED MATERIALS DATABASE FILE

- To load a previously saved database file, click the **Open Database** button.
- To retrieve a material, select it from the drop-down menu. The name and properties appear in the edit boxes.
- Click **Accept** to load the parameters into the **Globals** or **Layers Page**. To clear the material, click **Reject**.

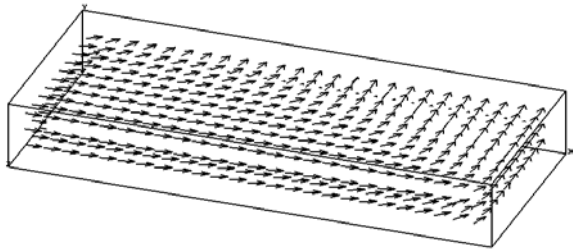
MANAGING THE MATERIALS DATABASE

The files are ASCII and can be edited with the LLG File Editor, Notepad, WordPad or a word processor. Once a database file has been loaded, the material properties remain in the drop-down menu until you finish the problem. You can delete any item by selecting it from the list, then clicking the **Delete Item** button. Clicking the **Delete All** button clears the entire list. You can enter up to 1,024 materials into a single database file; you can have as many database files as you wish.

Once data has been entered, you must click the **Accept** button for the data to change the LLG data structures. If you do not, you will lose your changes when you leave this property page. Click the **Main Control** button to return to the **Input Data Sheet-Main Page** at any time, but remember to click **Accept** before leaving this page to change data.

CHAPTER 9

Inputting Data into LLG- Boundary Conditions



You can specify **Boundary Conditions** uniformly on any or all of the six sides of a 3D Cartesian structure, and on the left and right sides of a 2D structure. When boundary conditions have been specified, the boundary elements are exchange-coupled to the **Simulation Volume**. If any of the boundary condition magnetization components are normal to the boundary surface, the magnetostatic stray field from the elements are computed and added to the energy. This stray field can be visualized in the **Simulation Sheet,** discussed later in the Manual. The boundary condition inputs include:

DESCRIPTION	VARIABLE	LIMITS
Left X = 0	m_i	$-1.0 \leq m_i \leq 1.0$
Right X = N_x	m_i	$-1.0 \leq m_i \leq 1.0$
Front Y = 0	m_i	$-1.0 \leq m_i \leq 1.0$
Back Y = N_y	m_i	$-1.0 \leq m_i \leq 1.0$
Bottom Z = 0	m_i	$-1.0 \leq m_i \leq 1.0$
Top Z = N_z	m_i	$-1.0 \leq m_i \leq 1.0$

The boundary condition direction cosine values can be unnormalized, as LLG performs this task internally. The values are constrained to $-1.0 \leq m_i \leq 1.0$.

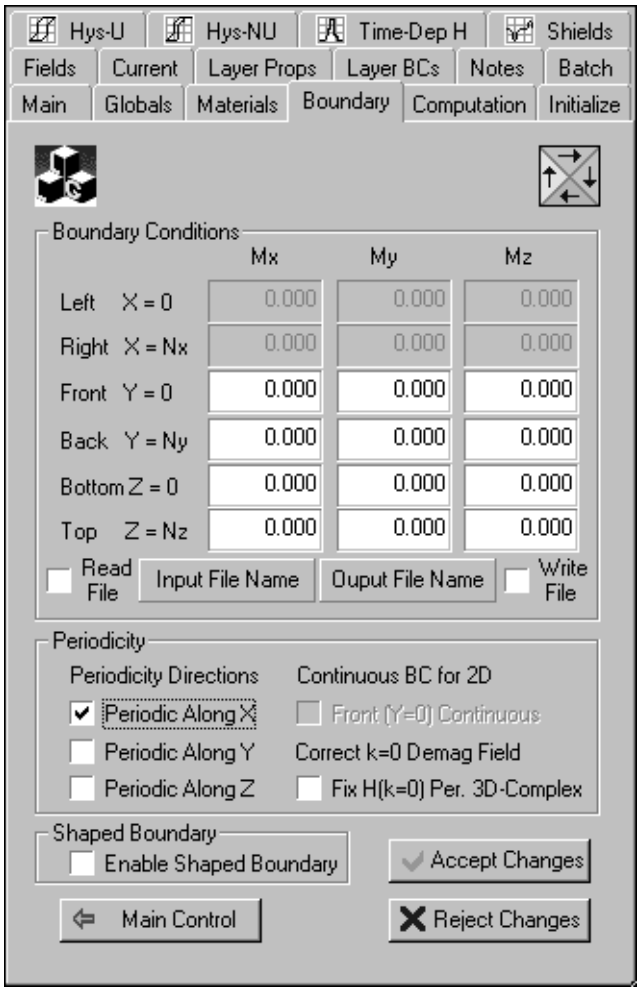


FIGURE 38. Input Data Sheet - Boundary Page

CREATING POSITION-DEPENDENT FILES

You can use LLG to generate position-dependent magnetostatic fields, such as those provided to an AMR sensor head by an external biasing permanent magnet. LLG computes the field for any set of boundary conditions where the moments are perpendicular to the boundary; therefore, you can use the boundary conditions to generate position-dependent fields for other calculations. Alternatively, you can generate formatted position-dependent field files and read them in with the **Boundary** or **Layer BCs Pages**.

Biasing a Structure with an External Field

If you want to bias a structure with an external field that is generated by magnets:

1. Set up the parameters for the internal grid of interest.
2. Make the material properties of the grid those of the permanent magnet, especially the magnetization. For example, if the magnets lie at X = 0 and at X = X_{max} and are magnetized along +X, set m_x (left) = 1.0 and m_x (right) = 1.0 and be sure that M_s on the **Globals Page** is that of the permanent magnet.
3. Check the **Write File** box; click **Output File Name** and name the file. **NOTE**: In general, you can read in or save a formatted position-dependent magnetic field by clicking the **Input File Name** or **Output File Name** button**.** To enable the read file or write file options, you ***MUST*** signal your intent to LLG by checking either the **Read File** and/or **Write File** boxes.
4. Be sure to click **Accept Changes** if you want to log the changes into the data structure. Once LLG has computed the field tensor, the field from the boundary conditions are computed and saved to file.
5. Exit LLG and restart your real problem; that is, the real sensor configuration.
6. Use the **Boundary Conditions Page** to read in the fields generated by the magnets. Do not enter anything into the boundary conditions fields. Close the page and proceed. You will be able to visualize the fields using the **Boundary Conditions Field Viewer** during the Simulation Phase.

Specifying Periodicity

LLG allows you to compute the properties of periodic structures. You can specify a three-dimensional structure to be periodic along any or all of the three Cartesian directions. This is implemented with FFTs. Two-dimensional simulations can be periodic only in Y. The continuous boundary condition affords you the option of modeling a bulk terminated surface, such as a domain wall, at the surface. In the LLG convention, continuous boundary conditions remove the magnetostatic charges from the bottom surfaces of the bottom row of sub-elements. Therefore, the magnetization appears continuous for all Y values below the bottom set of sub-elements. To implement this scheme, LLG uses the 2D-interface discretization scheme, as described earlier (see page 52) .

IMPORTANT NOTE: For **2D Real FFT**s, the number of cells in a periodic direction ***MUST*** be a power of two.

- **Periodic Along X**: Since the structure has wrap-around symmetry along X, the magnetostatic fields are periodic along X. For three-dimensional simulations, any or all of the directions can be selected, but periodicities are limited to two of the three dimensions at one time.
- **Periodic Along Y and Z**: The structure has wrap-around symmetry along Y and Z.

Specifying Continuous BC for 2D

A continuous boundary condition can be set in Y for a 2D simulation, which removes the boundary along the bottom side (Y = min), allowing a semi-finite (terminated) solid to be simulated. (**NOTE**: This feature is not presently implemented in v2, which is the same as in v1.)

Specifying Shaped Boundaries

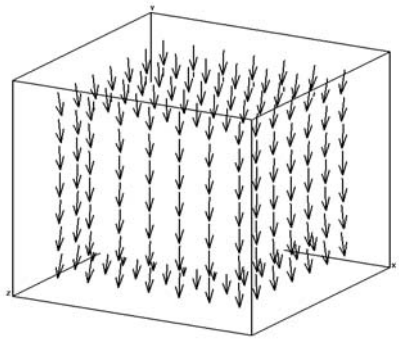
For many problems, LLG's stepwise approximation to the shaped boundaries changes the details of the switching behavior. To approximate the solution for shaped boundaries better, check the **Enable Shaped Boundary** box. This allows you to specify one globally shaped edge in the **Position Dependent Parameters Sheet**. However, this requires 8N extra sums in the computation of the demagnetization field. LLG computes the all orders demag field from the nearest neighbors that are shaped into n-gons (a hexagon is the largest number of sides). This type of solution allows you to get approximately the same coercive field for structures fixed to the grid or for structures rotated with respect to the grid. Refer to the material on Position Dependent Parameters (Chapter 22) for the operational details.

Fix H(k=0) Per. 3D-Complex

Use this option to fix the $k_{x,y,z}$=0 H-field in the periodic solution (usually less than 1 Oe). Must use 3D complex FFTs.

CHAPTER 10

Inputting Data into LLG-Computation



The **Computation Page** is for specifying the computational scheme for solutions. There is an energy minimization procedure that searches the grid point by point and a parallel (Fourier space) implementation of general LLG equation solvers. When you use parallel relaxation or time integration, output is defined in time. This page is for specifying **Convergence** and **Exit Criteria** (average or minimum) and the **Time Step** within the convergence radius limit. You can use an exchange/correlation (**Exchange/Corr.**) scheme for a problem that must be on a grid that is outside of the conventional micromagnetic limit.

IMPORTANT NOTE: For most problems, you can and should use the FFT Method for increased speed (that is, parallel solutions in time).

DESCRIPTION	VARIABLE	LIMITS
Energy SOR	SOR	$1 \le SOR \le 2$
Convergence	Δm	$0 \le \Delta m \le 10^7$
Iterations	N_{count}	$0 \le N_{count} \le 10^{10}$
Energy # Up	N_{up}	$1 \le N_{up} \le 100$
Number RHS	N_{rhs}	$1 \le N_{rhs} \le 10^2$
Gamma (MHz)	γ	$0 \le \gamma \le 10^{10}$
Alpha	α	$0 \le \alpha \le 2$
Start t (ns)	τ_1	$0 \le \tau_1 \le 10^8$
Stop t (ns)	τ_2	$0 \le \tau_2 \le 10^8$
Temp T (K)	T	$0 \le T \le 10^6$
RN Seed	I_{seed}	integral $0 \le I_{seed} \le 10^8$
Time Step (ps)	Δt	$10^{-6} \le \Delta t \le 10^8$
Exchange/Corr	$D_{exchange}$	$10^{-2} \le D_{exchange} \le 10^6$

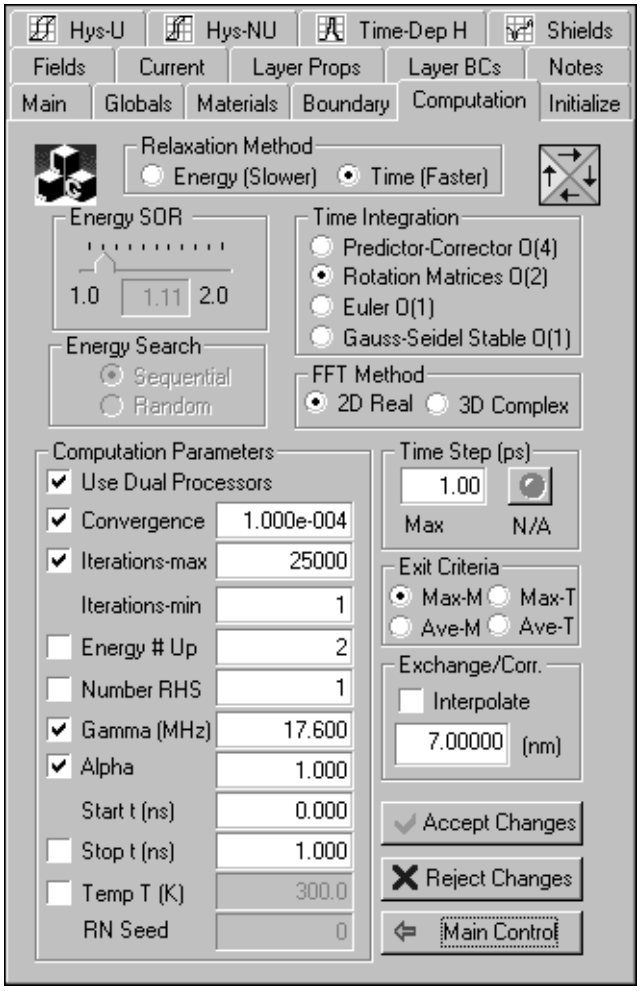


FIGURE 39. Input Data Sheet - Computation Page

RELAXATION METHOD

The energy minimization solver relaxes the magnetization one point at a time, which is done by rotating the magnetization towards or past the effective field vector within a sub-element, with the rotation constrained to be in the plane of those two vectors. This method is similar to solving the LLG equation in the limit of infinity-damping parameter α, since solutions take the form of torque = 0 at equilibrium. Aligning **M** to **H** forces the plane of rotation to include **M** and **H**, since there is no gyromagnetic precession term. Once you have rotated the vectors, the angles are normalized.

Advantages

There are two advantages to this method.

- First, the search can be implemented in an arbitrary sequence, which provides access to states not normally probed in a parallel-solution algorithm.
- Second, the eigenvalue for the solution to the differential equation leads to a more rapid convergence than the parallel-solution algorithm. For instance, the sample problem with the file name of 3D_sample1.llg_param solves for the magnetization in a 56 nm^3 ferromagnetic cube of fictitious Fe, beginning in a fixed planer vortex state. The sequential mode one-point method converges after 31 iterations, while the parallel LLG method with maximum step size and acceleration converges after over 130 iterations.

Disadvantage

The one disadvantage of the one-point method is that the CPU time depends on N^2 in the magnetostatic self-field computation. The **FFT Method** can be 100-1,000 times faster for large problems, even with a 10-100 times slower convergence in the differential equation itself. With the one-point method, the solution process can become unstable. Large oscillations and a convergence residual that never decreases are evidence of instability. In the worst cases of instability, the residual can reach 1.9-2.0. If this occurs while you are using this method, the only stabilization scheme is to stop the simulation and restart the problem with a finer (smaller sub-elements) grid.

When solving LLG directly:

$$(1+\alpha^2)\frac{\partial \vec{M}}{\partial t} = -\gamma \vec{M} \times \vec{H}_{eff} - \alpha\gamma \frac{\vec{M}}{M_s} \times (\vec{M} \times \vec{H}_{eff}) - \gamma \vec{M} \times \vec{\sigma} \sqrt{\frac{2k_B T \alpha (1+\alpha^2)}{\gamma M_S \Delta V \Delta t}} + \tau_{Spin-Torque}$$

α and γ can be adjusted independently to provide flexibility. Hence, both the gyromagnetic and damping terms are rigorously retained. You can solve the equation by using FFTs (O(N) fast), with all magnetization vectors rotating in unison. The rotations are performed using a simple Euler O(2) integration method, a rotation matrix (unitary transformations) in a reversible second-order in-time scheme O(2), or a Hamming Predictor-Corrector method O(4). The additional terms on the RHS of the LLG equation are the Langevin term at finite temperature T for gaussian random uncorrelated variates σ (σ_{rms} =1 at time step Δt in volume Δv in the Stratonovich sense) and the spin torque term (see Current Chapter).

ENERGY SOR

The over-relaxation parameter is used only in the LLG Energy Relaxation method. LLG uses a standard successive over-relaxation scheme to speed up convergence in one-point searches. An **Energy SOR** parameter of about 1.11, which is the default value, is nearly optimal for many systems. Experiment with the **SOR** slide bar and edit box to modify the parameter and to increase computation speed. A SOR parameter of 1.0 provides a straight relaxation. You can adjust the overrelaxation parameter using the slidebar or the edit box directly when **Energy (Slower)** has been checked.

ENERGY SEARCH: SEQUENTIAL OR RANDOM

For the one-point-at-a-time energy minimization method, specify either a **Sequential** or **Random** search by checking the appropriate button.

TIME (FASTER)

When the Landau-Liftshitz-Gilbert equations are being solved, time appears explicitly as a parameter. You can solve the equations directly in time by selecting an exit criterion associated with reaching equilibrium or by selecting an exit criterion at a specific time. Pure time methods are integrated for a fixed-time interval, whereas equilibrium time methods are generally focused on obtaining equilibrium magnetization states. When you select pure time integration, the program determines an approximate radius of convergence for the differential equations. This is presented as one maximum time step. The program warns you not to set the time step larger than this limit, as doing so makes the solution intrinsically unstable.

Linear differential equations can be integrated using implicit method integrators to achieve unconditional stability. Unfortunately, this is not the case with LLG equations, as they are coupled non-linear differential equations. A robust Gear's-method implicit integration scheme has been implemented in the program, but the maximum step size was not significantly larger than the stability limit for the explicit scheme. Since inverting and solving the Jacobian matrix slows down the calculation significantly, this method was abandoned. If your solution becomes unstable and oscillations occur, decrease the **Time Step** until stability is reestablished.

THE TIME STEP LIMIT IS PRIMARILY A FUNCTION OF THE EXCHANGE COUPLING PARAMETER, THE MAGNETIZATION AND THE SIZE OF THE SUB-ELEMENTS. PROBLEMS ON EQUIVALENT SYSTEMS SPECIFIED ON DIFFERENT GRIDS WILL HAVE INTRINSICALLY DIFFERENT TIME LIMITS. ENTER YOUR CHOICE FOR THE TIME STEP IN THE EDIT BOX PROVIDED.

TIME INTEGRATION

LLG supports four integrators.

- The crudest is an **Euler** Cartesian method, which is the fastest and least accurate.
- The **Rotation Matrices** method is the integrator of choice for solutions where alpha is greater than 0.5. In other words, when temporal dynamics are not being explored.
- The Cartesian **Predictor-Corrector** integrator is a modified Haming/predictor corrector, which is the most accurate of the three integrators (this scheme is a factor of two slower when alpha ~ 1 and can be about a factor of 50 faster when alpha ~ 0.01). ***Use this integrator for all problems where α < 0.5.***
- The **Gauss-Seidel Stable** method is a semi-implicit first-order integration scheme developed by Weinan E and co-workers at Princeton. The integration time steps can be much larger on fine grids using this method and is recommended for computations on extremely fine grids. LLG will not check your time step for stability when you use this method. You must experiment with a small problem at the same grid size to define the largest time step possible.

FFT METHOD

There are two FFT Methods.

You can unfold the symmetries in 3D to implement a true 3D real algorithm, but it is difficult. The advantage is that multi-thickness layers can optimize for the number of cells, which always translates into faster calculations. The danger is that the non-uniform treatment of the out of plane part, which is the driving force to torque the in-plane part. The BEST computations will use cubic pixels since there is no self-field biasing of any kind. However, for most systems, except those of theoretical interest, it is not pixel-efficient enough.

- Check the **2D Real FFT Method** button if your structure has fewer than five active layers in Z. This method is fastest if the number of pixels or elements in X and Y is a power of two. The **2D Real FFT Method** uses slices of real two-dimensional FFTs to perform the convolution in three dimensions. If your array is not a power of two, it will be padded.

  In the case that the layers are not the same thickness, use 2D Real FFT Method in each plane and sum. It is all-orders correct, with no approximations. This uses the Intel MKL FFT, which is power-of-two based and therefore is best for 2^n pixelated grids; otherwise, they are zero buffered.

IMPORTANT NOTE:

When you use periodic boundary conditions with the **2D Real FFT Method**, you must use a discretization that is a power of two in the direction of the periodicity.

- Check the **3D Complex FFT Method** button to perform complex 3D “factors of primes FFTs”. This method is intrinsically slower than **2D Real FFTs** for systems with few layers; however, it will be faster for true 3D structures.The advantage is that the factors of primes gets the size close with minimal buffering.

(PS) TIME STEP (MAX)

The Time Step must be selected to insure stability in the solution of the LLG equations. Once the simulation has been started, LLG computes the **Time Step** for the maximum radius of convergence for the problem. If your **Time Step** exceeds this value, you will be prompted to change it. Note that for many problems, you will want to select a **Time Step** smaller than the maximum Time Step. You might need to experiment with this parameter to tune it for your problem.

USE DUAL PROCESSORS

If your computer has dual processors, this feature will be enabled. If you want to use both processors, check the **Use Dual Processors** box.

COMPUTATION PARAMETERS

LLG uses **Computation Parameters** to solve the differential equations. With the exception of **Gamma**, **Alpha** and temperature (**Temp T**), the parameters help define an equilibrium magnetization configuration. Choosing an exit criterion that is too large can lead to erroneous results, so care should be exercised when you enter this parameter.

There are two simulation methods: relaxation and time integration. There are three exit criteria for the relaxation method and time limits for the time integration method. **Convergence**, **Iterations** and number of energy (**Energy # Up**) increases are the relaxation method exit criteria. Checking the box next to each criterion enables the edit box. You must select at least one exit criterion. However, if you select all three, the program will terminate the computation when the first exit criterion is reached. Each criterion that you check will be examined for exit.

CONVERGENCE

Enter the **Convergence** limit for exiting the calculation. This criterion is the absolute value of the change during the iteration process of any direction cosine component. For Permalloy structures with 10 nm cubic sub-elements, a convergence criterion between 1×10^{-4} and 3×10^{-4} should be suitable for most, if not all, problems. If you select **Average** for Convergence Criteria, the average of the absolute value of all deviations is checked against the exit criteria that you select. In this case, **Convergence** should be reduced by about 10 and would be between 1×10^{-5} and 3×10^{-5} for the above example.

ITERATIONS - MAX

Enter the maximum number of **Iterations** that the program should perform before it exits the calculation. LLG will end the simulation (or the simulation for the relaxation of a single field point in a hysteresis loop) if the number of function iterations is exceeded.

ITERATIONS - MIN

Enter the minimum number of **Iterations** that the program should perform. When you compute **Hysteresis Loops** and the field is changed by a small increment, the forcing function to move the magnetization from its equilibrium is very weak. Often a minimum of 100 **Iterations** is sufficient to allow LLG to begin to reorient the spins, which prevents a premature exit.

The iteration number is not as easy to select as you might think. The approach to equilibrium is governed by several factors, including the mesh size and density, but the slowest eigenvalue of the system ultimately determines how quickly the solution converges. Since LLG is non-linear, it supports soliton solutions. Near the coercive field, there is continuous slowing that can make the solution's convergence quite lengthy.

RECOMMENDATIONS FOR SELECTING CONVERGENCE

Check the **Convergence** and **Iterations** boxes. Set the **Convergence** to between 0.0001 and 0.0003 and set the **Iterations** to between 2500 and 10,000. Solve your problem a couple of times with different mesh sizes. Consult your *.llg_conv file to examine the iteration history or to see how the solutions evolve at low residuals. Reset these values so that they work better with the parameter values that you have selected. At the maximum **Time Step**, stable results have been found using Convergence = 10^{-4} and Iter = 5000 for systems composed of 5000-10000 10 nm^3 Permalloy sub-elements.

When to Use the Maximum Iterations Convergence Criteria

You would typically ***NOT*** use the **Maximum Iterations Convergence** criterion as a hard exit; however, it is useful for catching cases that will never meet the convergence exit criterion, such as when there is a loose spin in a corner. A loose spin will appear to oscillate in the effective field of its neighbor, due to the low coordination of its own spin environment. In such an instance, LLG will never meet the convergence exit criteria for maximum residuals; however, the spin configuration of the entire system might be well converged. It is for just this type of situation that the **Maximum Iterations Exit Criteria** was designed. Note that loose spins can be "tightened" by choosing a finer grid and by decreasing the time step.

Single Iterations

You should be aware that in LLG a single **Iteration** is one relaxation pass through the entire collection of sub-elements. For systems composed of between 5,000 and 10,000 sub-elements, setting the **Iterations** from between 2,500 and 10,000 yields effective results.

ENERGY # UP (ENERGY CRITERIA)

LLG has a damping term that guarantees that the energy of the system decreases with time. Instead of exiting at the convergence limit, you can enable LLG to exit when the energy begins to increase, that is, when the numerical precision of the problem has been reached. This is not independent of the **Time Step** and should be handled carefully. In the edit box, enter the number of sequential energy increases allowed before the simulation exits. You should choose a number greater than one (typically two), although LLG will accept one. When the mesh density is too coarse, you can exit LLG prematurely, since on a coarse grid the exchange energy density can deviate from its true value. Use this option with care to experiment with the precision with which you can determine the energy. Since the residuals are known with better accuracy than the energy density, they are a better measure as an exit criterion.

NUMBER RHS

LLG computes the effective field rigorously during each iteration cycle. Even when you use FFTs, the most time-consuming part of the computation is finding the demagnetization field. This parameter gives you a method for changing how often LLG computes the demagnetization fields during the solution process. In most systems, solutions are dominated by the long-range, low-spatial frequency demagnetization field, where setting **Number RHS** to anything but one can be disastrous. However, if your solution is really proceeding by domain wall motion far from the structure's edge, setting **Number RHS** to three or five will save you a factor of three or five in computing time. Experiment with this option carefully, keeping in mind that the solution is rigorous only when Numhs = 1, which is the recommended value.

GAMMA (MHZ)

This is the free electron gyromagnetic frequency. The most typical value is γ = 17.6 MHz/Oe. The check box enables or disables the inclusion of the gyromagnetic term in the torque equation. The default is selected.

ALPHA

This is the LLG phenomenological damping parameter (unitless). Since **Alpha** controls the time scale for the magnetization approach to the effective field direction, it governs how quickly a solution converges. The check box enables or disables the inclusion of the damping term in the torque equation. The default is selected. Real materials can have values of α in the 0.01 range; however, not much is known about the origin of this component of the relaxation (it is still a live issue). Setting **Alpha** to one provides the same final solution to identical problems (as α = 0.01 solutions) in a fraction of the computation time for domain wall systems that have been extensively tested. Also, the energy minimization method functions essentially as an α = large computation. Setting α to a value larger than one is not recommended. Experiment with a small α; for starters try α = 1

START T_1 (NS)

This is the starting time for a calculation in ns.

STOP T_2 (NS)

This is the ending time for a calculation in ns $T_1 \leq T_2 \leq 10^8$. Use these only for the **Time Integration** solution methodology and not for **Relaxation**.

TEMP T (K)

This is for activating the finite temperature solver. LLG features one finite temperature method, Langevin dynamics for the (quasi) time-based algorithms .R. Koch and G. Grinstein (IBM Yorktown Heights) have SOLVED the coarse graining problem to the finite temperature problem in micromagnetics using renormalization group methods. Please see *Physical Review Letters* **90**(20) 207201 (2003) to see how to rescale A, M, K and H at fixed temperatures if you know Tc.

RN SEED

When finite temperature calculations are required, a random number generator is used to generate gaussian random variables. The random number sequence is initialized with a random number seed, an integer. Internally, if you do not choose a random number seed, LLG will select one for you based upon the date and time that the simulation was

started. If you want to seed the same random number sequence for temperature dependent computations, fix the random number seed.

EXIT CRITERIA

There are four ways of exiting a calculation by satisfying the convergence criteria. You can specify that the residuals display one of the following during the simulation phase:

- The absolute value of the largest change in a single direction cosine (**Max-M)**.
- The absolute value of the average of all direction cosines **(Ave-M)**.
- The absolute value of the largest normalized torque (**Max-T)**.
- The absolute value of the average normalized torque (**Ave-T**).

For Permalloy structures composed of 5,000-10,000 10 nm^3 sub-elements, a maximum convergence criterion is rigorous if you set the exit criterion to between $1^{-3} \times 10^{-4}$ on the **LLG Input Sheet-Main Page**. However, if there are "loose" spins at an edge or corner, the simulation will not reach the exit criterion. For such cases, choose the **Average** exit criterion and set the **Convergence** limit to about 1/10 of the value used for the maximum method or $1^{-3} \times 10^{-5}$ for the above example.

EXCHANGE AND CORRELATION

Decreasing computation time without sacrificing the integrity of the rendered solution is a challenge. There can be a problem by which the physical size forbids using an appropriate mesh. In other words, sometimes there are not enough pixels to go around. This leads to the problem of coarse grids. When the discretization scheme is necessarily coarse, the exchange terms break down. All other micromagnetic effective fields are continuous variables. The demagnetization and anisotropy fields are length-scale invariant. The demagnetization fields have geometrical factors that change the value, but a uniformly magnetized cube has the same field in its center, no matter what size it is. However, in a micromagnetics context, the exchange field is defined as a second derivative, which means that the effective field scales with the mesh as $1/D^2$. This causes a problem and means that there is in fact a preferred discretization scheme, which, when implemented, is correct and gives proper dynamics. Furthermore, on coarse grids the approximation of continuous changes in M breaks down, that is, as an 180^0 wall distributed across two cells.

Artifacts of a mesh that is too coarse manifest themselves as switched lines of cells, that is, as arbitrary and unphysical 180^0 domain walls. They appear because this configuration, like total alignment, is torque-free. Methods are being tested to remove these artifacts from the program in a systematic, physical and rigorous way. An interim solution has been provided: introducing roughness or regularities necessarily breaks symmetry and alleviates the problem.

When you select **Exchange/Corr**, LLG linearly interpolates the magnetization onto a finer grid whose grid spacing is given by the correlation length. This changes the scaling of H_{ex} from $1/D^2$ to 1/D. This is non-physical since the exchange stiffness is unnaturally increased. Although you might be able to recover an equilibrium magnetization distribution, switching field studies (hysteresis loops) will not yield correct values.

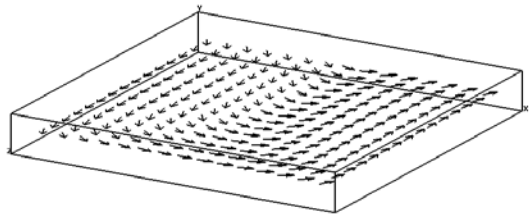
IMPORTANT NOTE:

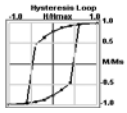
Do not use **Exchange/Corr** for hysteresis loops. It is only for finding an equilibrium magnetization state or for seeding a fine grid study.

Please remember to click the **Accept Changes** button if you wish your inputs to update the LLG parameters used in the calculation.

CHAPTER 11

Inputting Data into LLG-Initialization





The **Initialize Page** allows you to specify the initial (preconditioned) state of the simulation. Choosing the correct initial magnetization configuration can save time. For 2D and 3D cases, you can select a Random start. This Page gives you another opportunity to load a starting file as the initial condition. Note that, unless you have loaded an *.llg_dom file, sub-elements that are subjected to a pinning field are automatically initialized along the direction of the pinning field.

READ FROM FILE AND INPUT FILE NAME

The **Read From File** and the **3D Uniform**, **Transition** and **Vortex Magnetization** buttons are mutually exclusive. You can select only one. Once you select the **Read from File** option, you can input a file through the **Input File Name** button. This is the same as the **Read Angle Config** on the Main Page. Loading these angles from a file allows you to start with any predefined magnetization distribution or to continue a computation that may have been terminated prematurely. If the loaded file does not have the same discretization as the problem you wish to run, you will be prompted to indicate whether or not you want to interpolate the old data onto the new grid. In addition, you can explore the effect of changing input parameters or other input specifications on a particular equilibrium magnetization structure.

DESCRIPTION	VARIABLE	LIMITS
Theta	θ	$-180 \leq \theta \leq 180$
Phi	φ	$-360 \leq \varphi \leq 360$
Transition Number	$N_{transition}$	$1 \leq N_{transition} \leq 10$
Random Frac (All Cases)	f_{random}	$0.0 \leq f_{random} \leq 1.0$

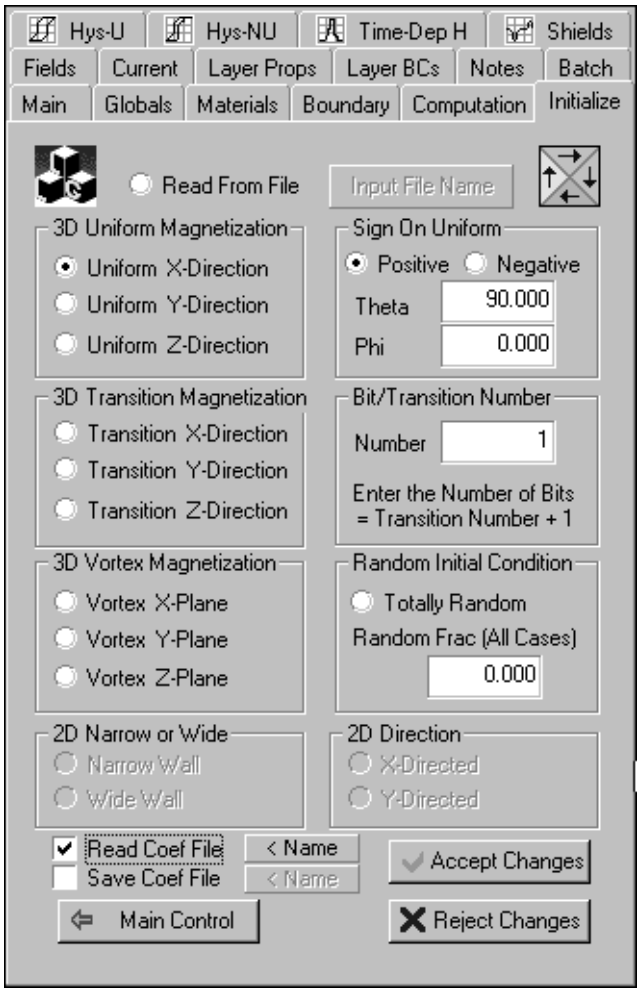


FIGURE 40. Input Data Sheet - Initialize Page

3D UNIFORM MAGNETIZATION

You can initialize the magnetization to be oriented uniformly along any of the three Cartesian directions by checking the appropriate button.

- The sign of the magnetization can be altered with the **Positive** and **Negative Sign On Uniform** buttons.
- Align the magnetization arbitrarily along any direction by modifying the entries in the **Theta** and **Phi** edit boxes.

The magnetization direction cosines in LLG are:

$$M_x = \sin\theta\cos\phi$$
$$M_y = \sin\theta\sin\phi$$
$$M_z = \cos\theta$$

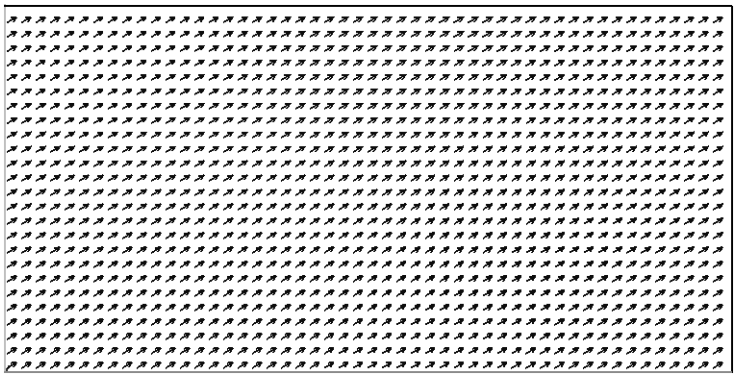


FIGURE 41. 1000 nm x 500 nm x 10 nm Permalloy Platelet Initialized with Uniform Magnetization

3D TRANSITION MAGNETIZATION

You can initialize the magnetization in the form of written disk-media tracks. You can select the direction parallel to the magnetization and perpendicular to the transitions by checking the appropriate option. Enter the number of transitions along that direction in the **Transition Number** edit box.

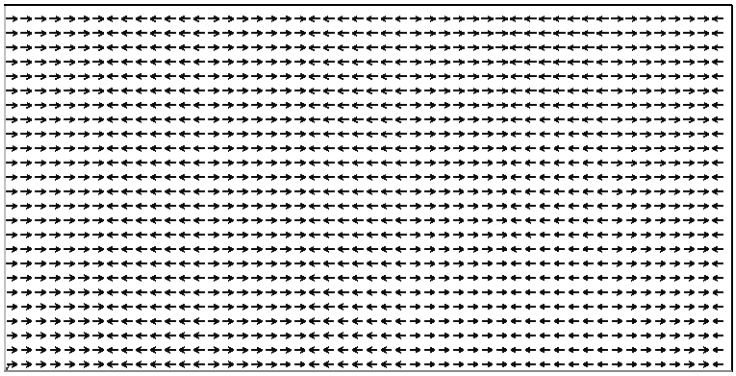


FIGURE 42. 1000 nm x 500 nm x 10 nm Permalloy Platelet Initialized with Transition Magnetization

3D VORTEX MAGNETIZATION

You can use a planer vortex to start the simulation. The flux closure pattern provided by a planer vortex is often one of the low energy states and can serve as the appropriate starting state. Care must be taken to ensure that the mesh discretization is fine enough not to pin the flux vortex core at the center. Select the plane of the vortex by checking the appropriate option. If the **Simulation Volume** has multiple planes, then all planes will be initialized in the same vortex state (except for pinned layers).

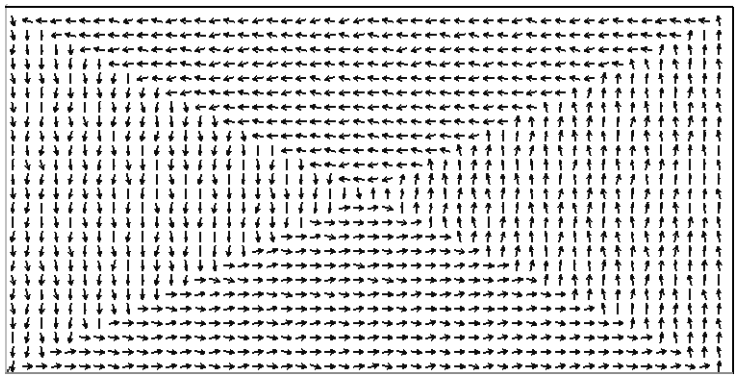


FIGURE 43. 1000 nm x 500 nm x 10 nm Permalloy Platelet Initialized with Vortex Magnetization in Y

2D NARROW OR WIDE

For 2D simulations of domain walls, you can select the initial transition region to occupy 20% (**Narrow**) or 100% (**Wide**) of the entire width of the discretized region.

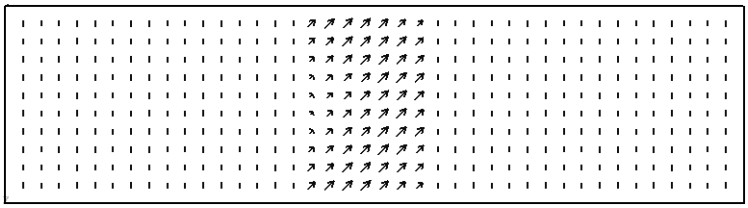


FIGURE 44. Two-dimensional 10 nm x 40 nm Permalloy Domain Wall, Narrow Initialization

RANDOM INITIAL CONDITION

You can select a completely random initial state by checking the **Totally Random** option.

For simulations at finite temperatures, a configuration with a **Random Fraction** of the magnetization can be selected (a number between 0 and 1.0). LLG uses a gaussian random number generator to superimpose a random component on top of the zero-temperature configuration selected.

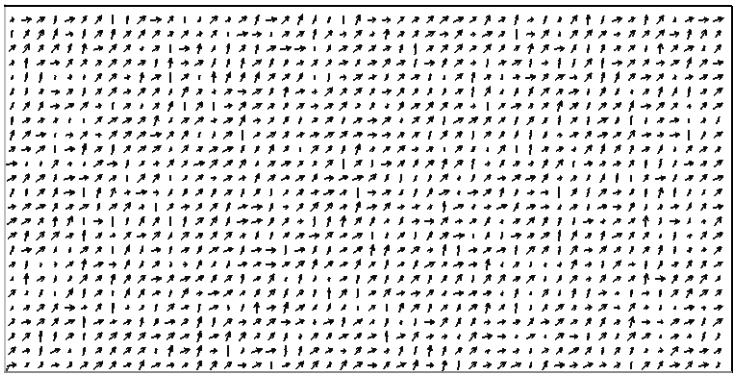


FIGURE 45. 1000 nm x 500 nm x 10 nm Permalloy Platelet Initialized with Totally Random Magnetization

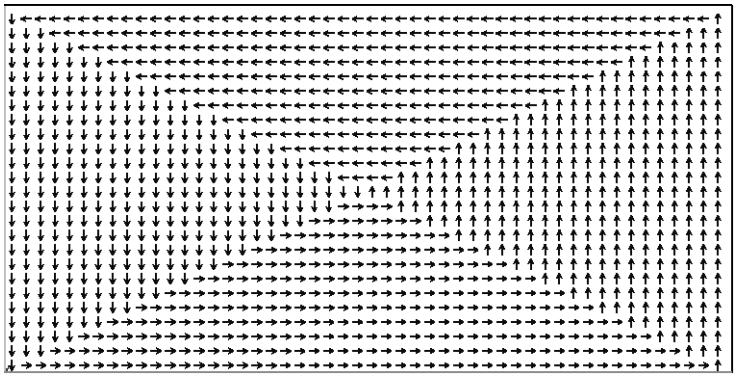
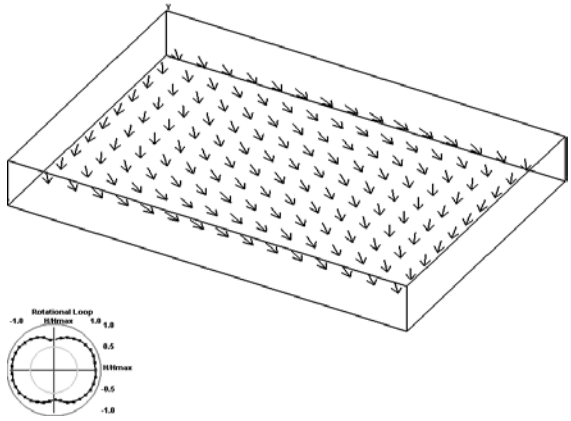


FIGURE 46. 1000 nm x 500 nm x 10 nm Permalloy Platelet Initialized with Vortex/Random Magnetization

Please remember to click the **Accept Changes** button if you want your inputs to update the LLG parameters used in the calculation.

CHAPTER 12

Inputting Data into LLG-Fields



The **Fields Page** allows you to specify any orientation of external fixed fields in which to minimize the magnetization of the sample, which is above and beyond those provided by the boundary conditions, currents and hysteresis fields. The external and pinning fields persist even if a hysteresis field is applied. This allows you additional flexibility in defining, running and interpreting problems and their solutions. External fields can be oriented uniformly along any direction. Pinning fields can be applied to any plane, in Y, of sub-elements, where the magnitude of the orientation can be independently selected for each pinned plane. In this way, a computationally efficient method allows coupling to antiferromagnetic substrates or to any other desired configuration.

EXTERNAL APPLIED FIELD

H_x is the X-component of the external field; H_y is the Y-component of the external field; H_z is the Z-component of the external field.

PINNING FIELD

H_x is the X-component of the pinning field; H_y is the Y-component of the pinning field; H_z is the Z-component of the pinning field.

PINNING A LAYER

You can pin a layer by entering a number into the **Layer to Pin** edit box (single discretized pixel layer to pin in Z) or by clicking the arrow keys on the scroll bar. You can scroll through the pinned layers to make changes. You ***MUST*** click the **Load H-Pin** button for your changes to take effect.

Please remember to click the **Accept Changes** button if you want your inputs to update the LLG parameters used in the calculation.

ANALYZING THE (K=0) FOURIER COMPONENT IN PERIODIC 3D COMPLEX BC COMPUTIONS

The (k=0) components of the field are evaluated on the Fields Page during the simulation process if this option has been selected on the Boundary Condition Page.

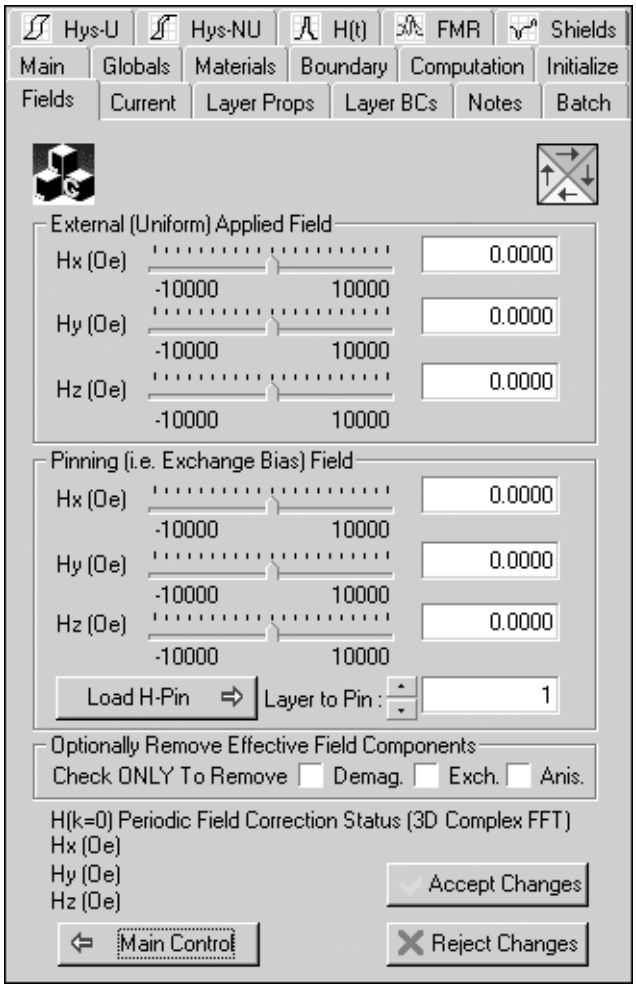


FIGURE 47. Input Data Sheet - Fields Page

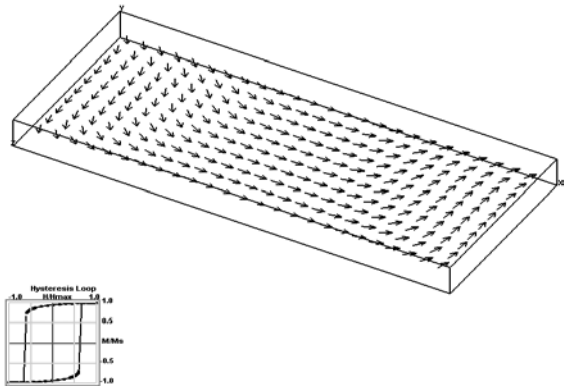
The pinning fields are entered in **Oe** as specified below:

DESCRIPTION	VARIABLE	LIMITS
External Applied Field	H_{ext}	$-10^6 \leq H_i \leq 10^6$
Pinning Field	H_{pin}	$-10^6 \leq H_i \leq 10^6$

OPTIONALLY REMOVE EFFECTIVE FIELD COMPONENTS

The Demag, Exchange and Anisotropy components to the effective field can be removed by checking the appropriate check box. This allows analytic treatments of micromagnetics to be compared with results from LLG (since demagnetization fields are rarely if ever included in analytic treatments.)

Inputting Data into LLG-Current



The **Current Page** is where you specify input currents. Input current can be specified to flow in two or three dimensions. For two dimensions, the current is injected along one axis of the structure. The current that flows along each current filament is a result of computing the series and parallel resistance along the straight paths to the other end of the structure. Current will flow only along the specified axis. When 3D currents are required, LLG computes the current flow using finite differences. 3D current requires complex data specification and memory must be committed. A description of the variables is given below, and a view of the I**nput Data Sheet-Current Page** is shown on the following page.

DESCRIPTION	VARIABLE	LIMITS
Current (μA)	I_{dc}	$0.0 < I_{dc} \leq 10^6$
ac Current (μA)	I_{ac}	$0.0 < I_{ac} \leq 10^6$
b Current Frequency (1/ps)	b	$0.0 \leq b \leq 10^6$
c Current Time Shift (ps)	c	$0.0 \leq c \leq 10^6$
t_1 ac Start Time	t_1	$-10^6 \leq t_1 \leq 10^6$
t_2 ac Stop Time	t_2	$-10^6 \leq t_2 \leq 10^6$
I(T-1) (μA) Current Start	I(T-1)	$-10^6 \leq I(T\text{-}1) \leq 10^6$
I(T-2) (μA) Current Stop	I(T-2)	$-10^6 \leq I(T\text{-}2) \leq 10^6$
Time Interval (Steps)	T_{steps}	$0 \leq T_{steps} \leq 16383$
Time Interval Specified	N	$0 \leq N \leq 1000$
Time(ps)/Step	T_{step}	$0.0 \leq T_{steps} \leq 0^6$

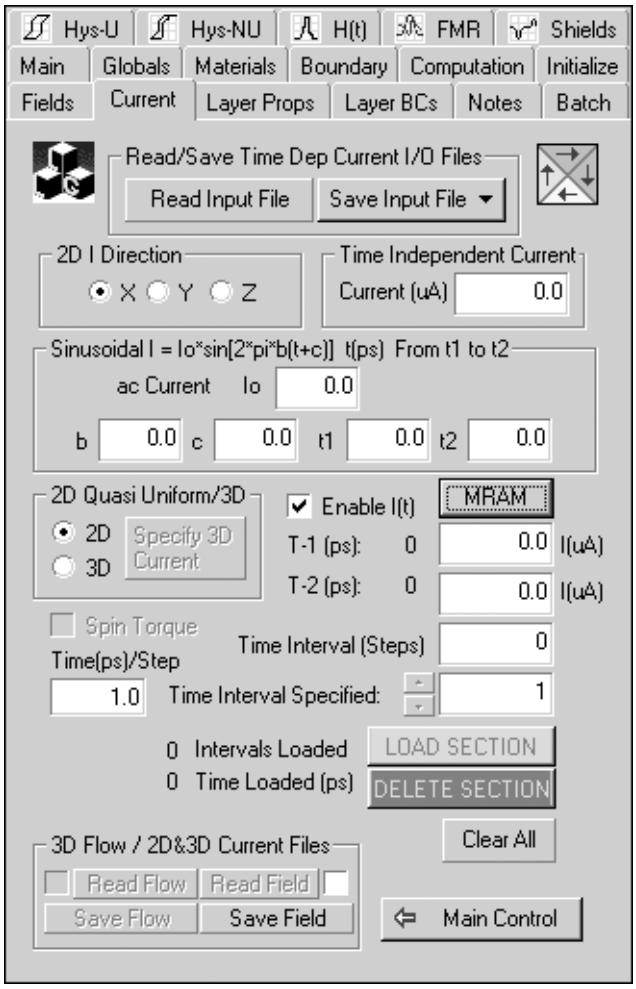


FIGURE 48. Input Data Sheet - Current Page

Reading and Saving Time Dependent Current Input and Output Files

LLG allows you to save and recall current sequences that you create using the **I Mask Editor**. A graphical representation of your data appears in the OGL window as you specify your current data. When you are satisfied with the time sequence, save your data by clicking the **Save Input File** button or recall your data using the **Read Input File** button.

Specifying a Time Independent Current

You can specify a current in microamps for 2D current flow. This current will be the 2D constant current when **Time Dep Current** is not selected. In this case, the **2D I Direction** will indicate down which axis the current will flow.

Specifying a Time Dependent Current

You can enter a time-dependent current (for both 2D and/or 3D currents) using the **I Mask Editor**.

1. First, you ***MUST*** check the **Enable I(t)** check box to activate the time-dependent current mode. In the 2D case, the current will flow down the axis specified by the **2D I Direction**. When time-dependent currents are active, you can specify a time-dependent current signal that may persist for up to 16ns. The time-dependent currents are input in intervals.
2. Specify the time interval in the **Time Interval Specified** edit box, starting with the first. Once you have specified all of the time intervals, you can use the arrow keys to scroll through them and to examine the specifications.
3. Specify the current limits at the end-points (time-limits of the current step) in microamps in the **T-1 (ps)** and/or **T-2 (ps)** edit boxes. Times are entered in picoseconds (ps).
4. Specify the number of time steps in the **Time Interval (Steps)** edit box.
5. Specify the time step itself in the **Time(ps)/Step** edit box. Only one time step is allowed for all time intervals; that is, it is a fixed time step calculation of the current. *NOTE: IF YOU USE BOTH TIME DEPENDENT CURRENT AND TIME DEPENDENT FIELDS, BE SURE THAT THE TIME STEPS ARE IDENTICAL.*
6. You ***MUST*** load the field section by clicking the **LOAD SECTION** button. Each section must be loaded, since the same controls are used both to examine and to modify the field values.
7. Increment the **Time Interval Specified** counter and enter the data for the next field sector.

While editing the time-dependent field sections, click **DELETE SECTION** to remove field points from the hysteresis loop. Remove all the specified **Time Intervals** by clicking the **Clear All** button.

Superimposing Sinusiodal I

You can superimpose a sinusoidal current on the time-dependent current, by specifying the following:

- The ac-current **Io** in microamps.
- The frequency in **b** in 1/ps.
- The time shift **c** in ps.
- The starting **t1** and stopping **t2** times in ps.

Specifying Spin-Torques

In 1996, John Slonczewski wrote a paper (JMMM **159** (1996) L1-L7) where spin-torques resulted from a direct interaction between spin dependent current generated in a ferromagnetic layer (polarizer) incident upon a second ferromagnetic layer (analyzer) through a paramagnet. The spin-torque check box allows you to include spin-torques in your computation. These spin torques are only active for 2D currents oriented in the Z-DIRECTION. In addition, the polarization (P) and magnetization must be finite in the layers adjacent to the paramagnet, defined as having M=P=0.

LLG Micromagnetics Simulator implements the spin-torques according to the following equation:

$$\partial \vec{m}_{1,2} / \partial t = \vec{m}_{1,2} \times (\vec{m}_1 \times \vec{m}_2) \gamma \frac{hJg_{1,2}}{2\pi e \Delta_{1,2} M_{1,2}}$$

Here, the magnetizations, 1 and 2, are sequential along positive z, J is the current density, h is Plank's constant and e is the electronic charge. Since this is an interface torque, the Δ in the denominator is the thickness of the layer adjacent to the interface. When J is given in Amp/cm^2 and e in coulombs, the units are cgs and the post factor has units of a field. The function g is given by Sloncewski as follows:

$$g = \frac{4P^{\frac{3}{2}}}{(1+P)^3(3+\vec{m}_1\cdot\vec{m}_2)-16P^{\frac{3}{2}}} \Rightarrow \frac{4P_1P_2^{\frac{1}{2}}}{(1+P_1)^2(1+P_2)(3+\vec{m}_1\cdot\vec{m}_2)-16P_1P_2^{\frac{1}{2}}} = g_1$$

and P = 0.40, 0.35, 0.23 and 0.12 at T=4K for Fe, Co, Ni and Gd respectively.

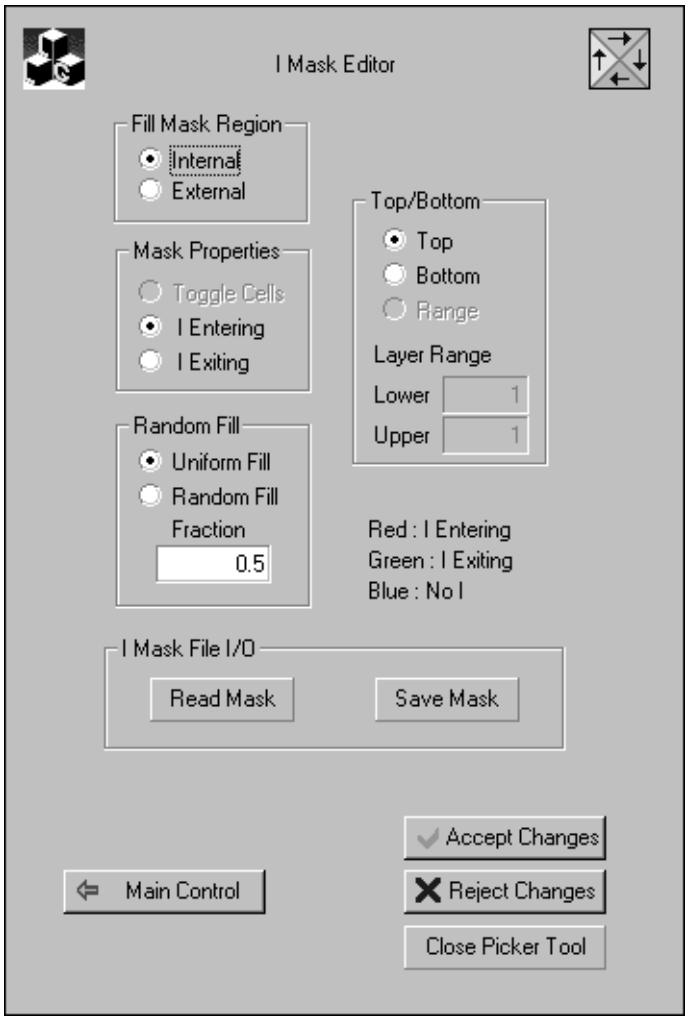


FIGURE 49. Input Data Sheet - (Current) I Mask Editor

SELECTING 2D QUASI UNIFORM OR 3D CURRENTS

You can select **2D Quasi Uniform** currents or true **3D** currents.

IMPORTANT NOTE:

When you select **3D** currents, you ***MUST*** specify the input and output regions for the current flow for current conservation to work! To do this, click the **Specify 3D Current** button, which activates the (current) **I Mask Editor**.

SPECIFYING REGIONS OF ENTRY AND EXIT FOR 3D CURRENT

Using the **Current Editor**, you can specify regions of entry and exit for the current. You can use the mask tools (see Chapter 21).

1. Using the mouse, draw the region that bounds the entry or exit point for the current.
2. Fill the **Internal** or **External** portions of the region with current by selecting the appropriate **Fill Mask Region**.
3. Define whether the current is entering (**I Entering**) or exiting (**I Exiting**) the structure, under **Mask Properties**. **NOTE**: You ***MUST*** specify current entering and leaving the structure for current conservation to work!
4. Randomly or uniformly fill the region by selecting **Random Fill** or **Uniform Fill**. Specify the **Fraction** of the uniform variate that fills the region (that is, uniform random numbers are generated between 0.0 and 1.0 and the **Fraction** above the fraction entered is accepted for current paths).
5. For any given view projection, you can specify that the current enters or exits via the **Top**, the **Bottom**, or over a range as indicated in the **Lower** and **Upper** edit boxes.
6. Once you have created a current mask, you can **Save Mask**s or **Read Mask**s to binary files.
7. Please remember to click the **Accept Changes** button if you wish your inputs to update the LLG parameters used in the calculation.

READING AND SAVING 3D CURRENT FILES

When 3D currents have been specified, you can save or read the computed current flow. Since large sparse matrices take some time to solve, once you solve for a 3D current flow, you should reuse it. The current flow is stored for a 1 microamp test current. Internal to LLG, the fields are computed for that test current, and scaled by the appropriate constant or time-dependent current (linearity).

SIMULATING MRAM BIAS AND WRITE FIELDS

LLG includes a facility to add add time dependent MRAM fields. In order to activate the MRAM tool you must use a time dependent current, in this case the sense current. When you specify a time dependent sense current, the MRAM button will be enabled. On the MRAM dialog (shown below) two field pulses can be selected, a bias line pulse and a write line pulse. These labels serve only to identify the field pulses and you can naturally use them as you please. You can specify the direction and the magnitude {Hx,Hy,Hz] of each of the pulses and independently specify the rise (t_{rise}), fall (t_{fall}), peak (t_{peak}), end (t_{end}), and turn-on time (t_{on})of each pulse (relative to LLG's computation time and those naturally specified for the sense current timing). The temporal pulse shape is defined as H = f(t)[Hx, Hy, Hz] where f(t) is 0 when $t < t_{on}$, $(1-\exp(-(t-t_{on})/t_{rise})/(1-\exp(-(t_{peak}-t_{on})/t_{rise})$ when $t_{on} < t < t_{peak}$, and 1 $((1-\exp(-(t-t_{peak})/t_{fall})/(1-\exp(-(t_{end}-t_{peak})/t_{fall}))$ when $t_{peak} < t < t_{end}$, and 0 again when $t > t_{end}$. You can view the pulses with the simple viewer. Remember to accept your changes to activate the field pulses, and to check the check box at the top of the dialog to indicate this.

This tool should provide facility to explore pulse timing issues important in defining optimal MRAM device characteristics.

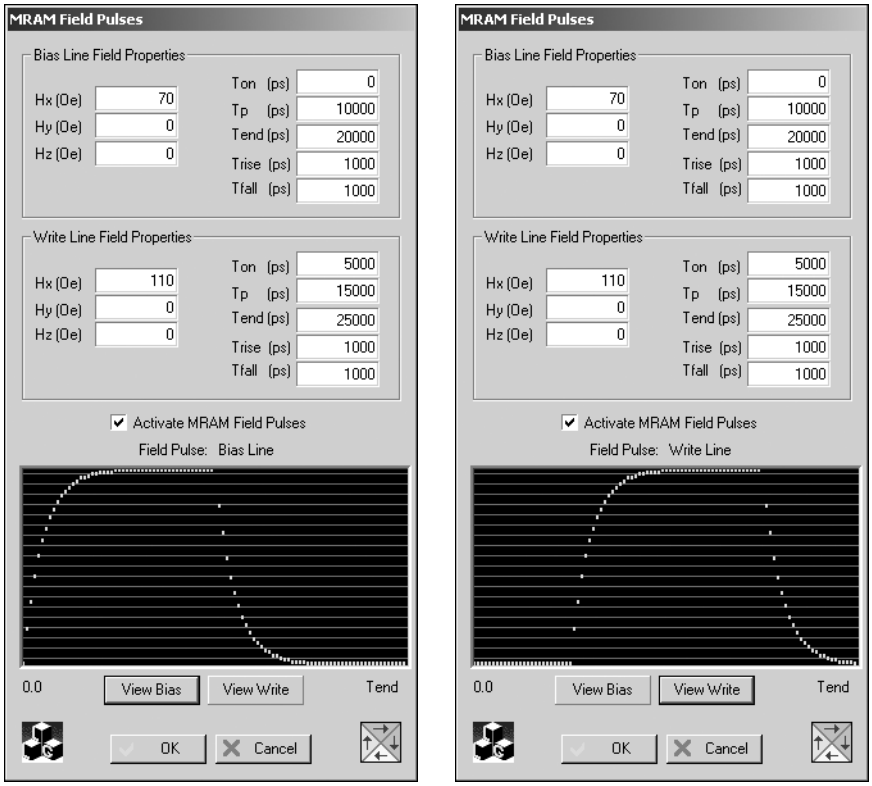
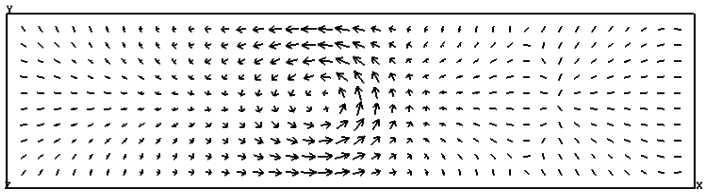


FIGURE 50. MRAM pulse Timing (bias-left and write-right).

CHAPTER 14

Inputting Data into LLG-Layer Properties



NOTE: Refer to the material on the **Global Page** (see page 54) for inputting elements that are common to the **Global** and **Layer Props Pages**, including Material Properties.

The program treats materials as piece-wise uniform. You must define the layer-specific (and the position-dependent) properties that describe the material or materials. A layer is distinct from a discretized sub-element or pixel in that, for the purposes of this program, it is any collection of pixels composed of an independent material. A layer is defined as a group of pixels, or sub-elements, that is composed of a single magnetic or non-magnetic material that is confined to that layer. In three-dimensional problems, layers are confined to the X-Y plane (Z normal); in two-dimensional problems, layers are confined to X-Z planes (Y normal), because structures in 2D are infinite in Z. A layer can be composed of one or several sub-elements in the normal direction.

At present the program can accommodate up to 1024 layers. However, when the Z discretization is fixed for 3D problems, the thickness of each layer must be an integral number of the pixel width in Z. If you check the **Non Uniform** box at bottom left of the page, this constraint is relaxed and the Z thickness of each layer('s pixel) need not be the same. However, for variable thickness layers, only the **2D Real FFT** method of computation is supported. Refer to Chapter 7 Globals for the variables.

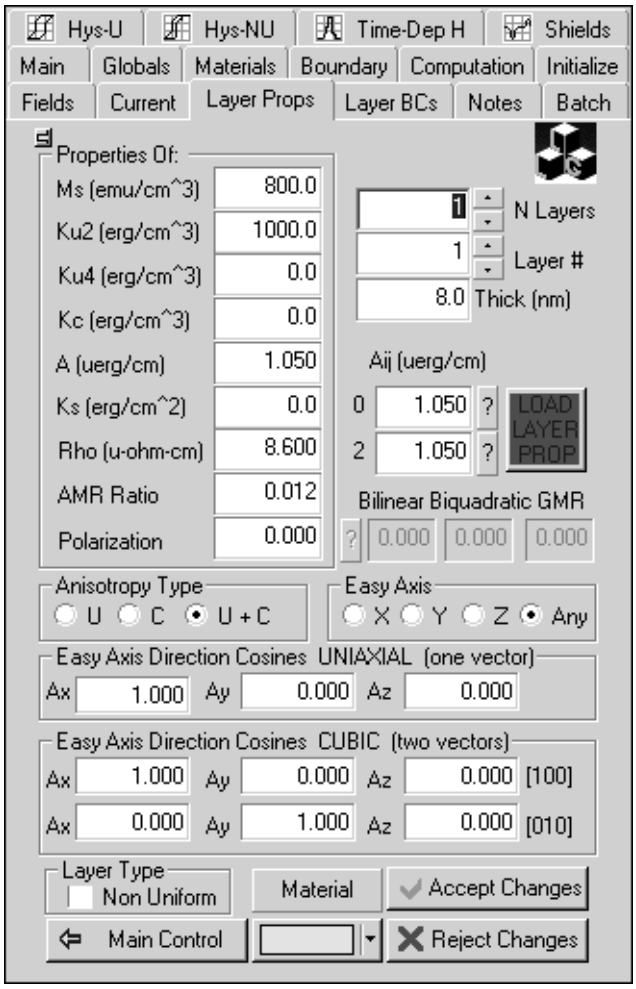


FIGURE 51. Input Data Sheet - Layer Properties Page

DESCRIPTION	VARIABLE	LIMITS
M_s (emu/cm^3)	M_S (emu/cm^3)	$0.0 < M_S \leq 10^6$
K_{u2} (erg/cm^3)	K_{u2} (erg/cm^3)	$-10^{10} \leq K_{u2} \leq 10^{10}$
K_{u4} (erg/cm^3)	K_{u4} (erg/cm^3)	$-10^{10} \leq K_{u4} \leq 10^{10}$
K_c (erg/cm^3)	K_c (erg/cm^3)	$-10^{10} \leq K_c \leq 10^{10}$
A (uerg/cm)	A (μerg/cm)	$-10^2 \leq A \leq 10^2$
K_s (erg/cm^2)	K_s (erg/cm^2)	$-10^{10} \leq K_s \leq 10^{10}$
Rho (μohm/cm)	ρ (μohm/cm)	$0.01 \leq \rho \leq 10^6$
AMR Ratio	AMR (%)	$0.0 \leq AMR \leq 1.0$
N Layers	N	$0 \leq N \leq 1024$
Layer #	N_{layer}	$0 \leq N_{layer} \leq 1024$
Layer T (nm) Thickness	T_{layer}	$0.01 \leq T_{layer} \leq 10^{10}$
0 (Load Layer A_{ij} (μerg/cm))	A_{ij} (μerg/cm)	$-10^2 \leq A_{ij} \leq 10^2$
2 (Load Layer A_{ij} (μerg/cm))	A_{ij} (μerg/cm)	$-10^2 \leq A_{ij} \leq 10^2$
Bilinear Coupling (μerg/cm)	$A_{bilinear}$ (μerg/cm)	$-10^2 \leq A_{bilinear} \leq 10^2$
Biquadratic Coupling (μerg/cm)	$B_{biquadratic}$ (μerg/cm)	$-10^2 \leq B_{biquadratic} \leq 10^2$
GMR (fraction)	GMR	$0.0 \leq GMR \leq 10.0$
Polarization	P	$0.0 \leq P \leq 1.0$
Easy Axis Direction Cosines UNIAXIAL (one vector)		
Ax x-projection	Ax	$-1.0 \leq Ax \leq 1.0$
Ay y-projection	Ay	$-1.0 \leq Ay \leq 1.0$
Az z-projection	Az	$-1.0 \leq Az \leq 1.0$
Easy Axis Direction Cosines CUBIC (two vectors)		
Ax (100) x1-projection	Ax (100)	$-1.0 \leq Ax\ (100) \leq 1.0$
Ay (100) y1-projection	Ay (100)	$-1.0 \leq Ay\ (100) \leq 1.0$
Az (100) z1-projection	Az (100)	$-1.0 \leq Az\ (100) \leq 1.0$
Ax (010) x2-projection	Ax (010)	$-1.0 \leq Ax\ (010) \leq 1.0$
Ay (010) y2-projection	Ay (010)	$-1.0 \leq Ay\ (010) \leq 1.0$
Az (010) z2-projection	Az (010)	$-1.0 \leq Az\ (010) \leq 1.0$

DEFINING LAYER PROPERTIES

1. Select the **Layers** option under **Structure Properties** on the **Main Page** to enable the **Layer Props Page**. Then, click the **Layer Props** tab.
2. Input the number of layers of your entire structure in the **N Layers** box. For the fixed-layer thickness method, this is the total number of different material layers (sub-pixels are defined within each layer as needed).
3. If you check the **Non Uniform** box at the bottom left under **Layer Type**, each single pixel width layer will have the thickness that you specify, and the number of discretized sub-elements in Z will be the total number of layers. In this case, inside of LLG demag fields in each 2D sheet are computed using **Real 2D FFTs** and are directly summed in real space in Z.

For each layer for which you want to define the properties:

4. In the **Layer #** edit box, indicate the layer for which you want to set the properties.

> **IMPORTANT NOTE FOR 1-LAYER POSITION-DEPENDENT STRUCTURES:** If you plan on creating a 1-layer structure with position-dependent properties, you still ***MUST*** define the structure as 1-layer on the Layer Props Page according to the instructions here. In this case, the layer thickness (defined on the Layer Props Page) and the total thickness of the structure (defined on the Main Page) are equal.

5. Input the thickness of the indicated layer in the **Layer T(nm)** box.

> **IMPORTANT NOTE:** The total thickness of your structure must equal the thickness of your structure for the uniform option. Further, for the uniform option, since the structure is discretized into a uniform mesh in Z, each layer must contain an integral number of sub-elements. LLG will not let you proceed unless these criteria are met.

6. Enter all of the parameters for the indicated layer.
7. To ***apply a color*** to the indicated layer to distinguish it from other layers graphically, select a color from the **drop-down color box** at the bottom center. If you want to make a custom label for the layer, click the small yellow arrow at the upper right to access the **Material Label** menu.

THE NEXT THREE STEPS MUST BE FOLLOWED PRECISELY OR YOUR INPUT WILL NOT TAKE EFFECT

8. Once you have specified all of your parameters for the indicated layer, you ***MUST*** click the **LOAD LAYER PROP** button for your entries to be recorded. Once you have loaded a layer's properties, the background color of that layer's edit field changes from white to yellow.
9. ***REPEAT*** steps 2 through 5 for each layer, making sure that you click the **LOAD LAYER PROP** button each time before proceeding to the next layer.
10. Once you complete the data entry for all of the layers, you ***MUST*** click **Accept Changes** for the input of all of the layers to take effect.

SPECIFYING THE A_{IJ} INTERLAYER

LLG uses the convention that the exchange stiffness between adjacent cells can be modified. This is particularly important when there is an interface between dissimilar materials. For 3D systems where layers occur with Z-directed normals, you must independently specify how a material layer will couple across the interface. LLG provides you with the flexibility to make the assignment with the **A_{IJ}** interlayer. For example, suppose your layered structure has a dirty evaporator that creates carbon at the interface, which greatly reduces or eliminates the coupling. This would allow you to put real coupling across the interface. A_{IJ} Bilinear is the coupling across a non-magnetic layer. This is the GMR type of coupling that can be ferro- or antiferro depending on the thickness of the interlayer.

You can modify the coupling between adjacent layers. Assuming that the layer specified is layer 2 in a 3-layer system, you can specify the exchange coupling between layer 2 and layers 1 and 3, that is, **A_{12}**, in the edit box next to the number of the layer to couple to, in this case layer 1 or 3. To modify the exchange between layer 2 and layer 1, alter the number in the edit box next to the 1. Interlayer exchange operates only between adjacent layers. To modify interlayer exchange across non-magnetic interlayers, use the **Bilinear** or **Biquadratic** exchange fields.

MODIFYING BILINEAR AND BIQUADRATIC INTERCOUPLING AND GMR

You can modify the **Bilinear** and **Biquadratic** exchange across non-magnetic spacers, as in Co/Cu GMR superlattices. When you know the exchange field rather than the exchange coupling parameter, ***calculate the exchange bias*** (see below). Use the bilinear and biquadratic coupling coefficients only to couple films across a non-magnetic layer, which has $M_S = 0$. For example, the edit boxes are disabled if you specify a three-layer system with a central magnetic layer.

There are many paradigms for specifying the coupling across non-magnetic layers. In LLG, the topmost sheet of sub-elements in the layer below the non-magnetic layer couples to the bottommost sheet of sub-elements in the layer above the non-magnetic layer. Since the exchange field, sub-element discretization and exchange coupling parameters are related in LLG, an independent assignment of the exchange field and the exchange parameter is impossible. In LLG, the fundamental exchange parameter is A rather than the exchange field. The exchange parameter couples adjacent sub-elements using a finite-difference second derivative to determine the exchange field. Sub-elements within layers are strongly exchange coupled, while sub-elements across non-magnetic spacer layers are typically weakly coupled. Bilinear or biquadratic exchange between sub-elements forces the coupling between the layers. With this LLG convention, the bilinear and biquadratic coupling energy density is

$$E_{ex} = \int A_{bilinear}(1 - \hat{m}_i \cdot \hat{m}_j) + B_{biquaratic}(1 - (\hat{m}_i \cdot \hat{m}_j)^2)dv$$

where $A_{bilinear}$ is the bilinear coupling coefficient, $B_{biquadratic}$ is the biquadratic coupling coefficient, and m_i and m_j are the direction cosines adjacent to the non-magnetic spacer layer. The bilinear and biquadratic exchange fields are defined in terms of the appropriate derivatives with respect to magnetization, thereby introducing a sub-element-size dependence into the exchange field.

CALCULATING THE EXCHANGE BIAS

In LLG Micromagnetics Simulator, exchange energy density is defined as

$$E_{ex} = \int (\nabla m)^2 dv$$

where A is the exchange stiffness in erg/cm, ∇ is the gradient operator, m_i is the direction cosines, and dv is the volume element. LLG implements this exchange integral on a finite-difference grid with piece-wise uniform variables. Hence, the effective field, due to exchange on a given cell, is (uniform cubic grid):

$$\vec{H}_{ex} = \frac{-\partial E_{ex}}{\partial \vec{M}} = \frac{2A}{M_s \Delta^2}(\hat{x} m_x + \hat{y} m_y + \hat{z} m_z)$$

Thus, the exchange effective field scales as $2A/M_s\Delta^2$ and the direction cosine of the nearest neighbor. The exchange field strength for adjacent pixels across a layer is

$$\vec{H}_{ex} = \frac{2A}{M_s \Delta^2}\hat{m}$$

where M_s is the magnetization in the layer of interest and is the direction cosine across the interface layer. Therefore, the exchange coupling parameter can be calculated as $A_{ex} = M_s\Delta^2 /2$ H, as a function of the exchange field and discretization. This is the protocol used in LLG.

SPECIFYING THE ANISOTROPY TYPE

The anisotropy types are Cubic (**C**), Uniaxial (**U**) or both (**U+C**). When the system is not layered (see below), the anistropy is uniform throughout the simulation structure.

- For **Uniaxial** anisotropy, the **Easy Axis Direction Cosines** are enabled. Enter the direction of a vector along which the easy axis will be oriented. For this, you need to enter one vector or direction only. You need not normalize the vector (you can enter components between -1 and 1), as the program does this for you. For example, if you enter 1, 1 and 1, click **Accept Changes**, exit and re-enter the page, the selections appear as 0.57, 0.57 and 0.57.
- For **Cubic Anisotropy**, the cubic options are enabled. This is somewhat more complex, since a plane or two directions must be specified. You must enter two orthogonal vectors, because the symmetry is perfect cubic. The program will set them to $A_{x1}\,A_{x2} + A_{y1}\,A_{y2} + A_{z1}\,A_{z2} = 0$. The third vector is defined internally from the cross product. In principle, you can define any direction, as long as the orthogonality condition for the cubic case is fulfilled.
- If you select **C + U**, both options are enabled and must be defined.

SPECIFYING THE EASY AXIS: X, Y, Z AND ANY

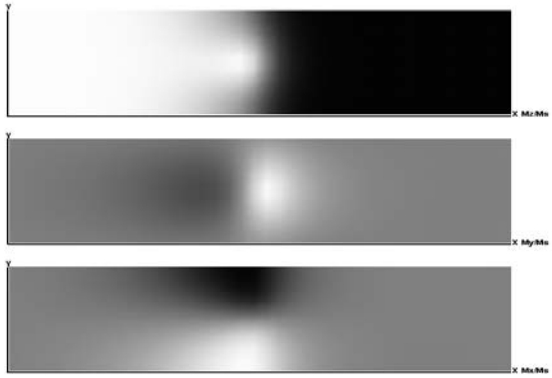
You can specify the direction of the easy axis using either the **X**, **Y** or **Z** buttons or by selecting the **Any** button and entering the vector's direction in the easy axis direction cosine vector A_i directly.

CONVENTION FOR BULK, INTERFACE AND SURFACE ANISOTROPY COEFFICIENTS

When the anisotropy coefficients are positive, the internal energy due to anisotropy will always be positive. The Uniaxial energy density is written as $E_u=K_{u2}(1-(\underline{m}.\underline{\alpha})^2) + K_{u4}(1-(\underline{m}.\underline{\alpha})^4)$, where $\underline{\alpha}$ is a unit vector along the easy direction. The interface anisotropy has the form $E_i =1/2K_s(\underline{m}.\underline{m})$. The interface effective field is simply $-K_s\underline{m}$, which favors out-of-plane magnetization when K < 0. This is the convention in LLG.

CHAPTER 15

Inputting Data into LLG-Layer Boundary Conditions



The **Layer Boundary Conditions Page** allows you to define external sources for the differential equation. These boundary conditions are identical in function to the Global Boundary Conditions described in Chapter 9. However, when you select a problem with layers, you can specify Boundary Conditions for each layer individually. For example, in a magnetic sensor problem, you might have a permanent magnet abutting the lower half of the stack. A simple way to simulate a permanent magnet is to specify boundary conditions with the magnetization of the boundary pointing along the direction that the permanent magnet is magnetized. If the magnet is not exchange coupled to the stack, simply use the mask tool to isolate the sensor from the boundary with dead ($M_s = 0$) cells. The table below summarizes the input variables. The **Input Sheet-Layer BCs Page** is shown on the following page. As in the **Global Boundary Condition Page**, you can read boundary condition files by checking the **Read File** box and selecting a file name using the **Input File Name** button.

Once you have specified all of your parameters, you ***MUST*** click the **Load Layer BC** button for your entries to be recorded. Once you have loaded a layer's Boundary Conditions, the background color of the edit box changes from white to yellow. You must repeat this sequence for each layer as you enter the properties. Since LLG uses property pages and property sheets to record data sequences, you must signal LLG that your entries are to take effect. Thus, once you finish entering each layer's properties, you must click **Load Layer BC**. Once you complete all of your data entry, you ***MUST*** click **Accept Changes** for all of your layer changes to be permanently recorded. Note, since the layers are in z, the top and bottom layers do not change when you scroll through the layers.

DESCRIPTION	VARIABLE	LIMITS
Load Layer BC	N_{layer}	$1 < N_{layer} \leq N_{layers}$
Left X = 0	m_i	$-1.0 \leq m_i \leq 1.0$
Right X = N_x	m_i	$-1.0 \leq m_i \leq 1.0$
Front Y = 0	m_i	$-1.0 \leq m_i \leq 1.0$
Back Y = N_y	m_i	$-1.0 \leq m_i \leq 1.0$
Bottom Z = 0	m_i	$-1.0 \leq m_i \leq 1.0$
Top Z = N_z	m_i	$-1.0 \leq m_i \leq 1.0$

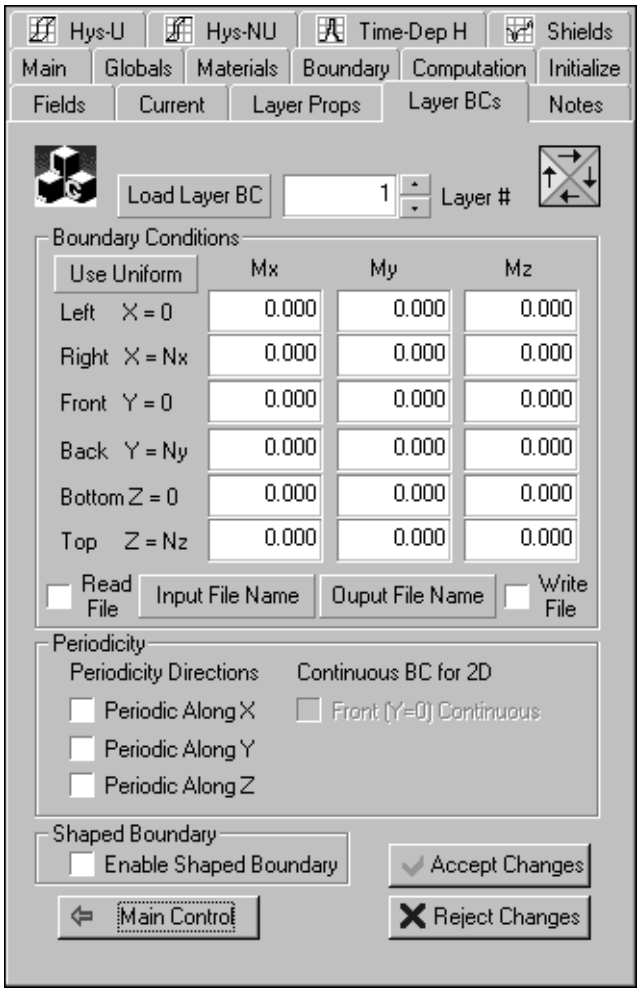


FIGURE 52. Input Data Sheet - Layer Boundary Conditions Page

SPECIFYING BOUNDARY CONDITIONS

You can specify **Diriclet Boundary Conditions** uniformly on any or all of the six sides of a 3D Cartesian structure, and on the left and right sides of a 2D structure. When boundary conditions have been specified, the boundary elements are exchange-coupled to the **Simulation Volume**. If any of the boundary condition magnetization components is normal to the boundary surface, the magnetostatic stray field from the elements is computed and added to the energy. You can visualize the stray field in the Simulation Sheet covered in Chapter 23. The boundary condition inputs are:

Left: Boundary Condition on X = 0 plane

Right: Boundary Condition on $X = X_{max}$ (N_x)

Bottom: Boundary Condition on Y = 0 plane

Top: Boundary Condition on $Y = Y_{max}$ (N_y)

Back: Boundary Condition on Z = 0 plane

Front: Boundary Condition on $Z = Z_{max}$ (N_z)

The boundary condition direction cosine values can be unnormalized, as LLG performs normalization internally. However, the values are constrained to $-1 \leq m_i \leq 1$.

Generating Position-dependent Files

You can use LLG to generate position-dependent magnetostatic fields, such as those provided to an AMR sensor head by an external biasing permanent magnet. LLG computes the field for any set of boundary conditions where the moments are perpendicular to the boundary; therefore, you can use the boundary conditions to generate position-dependent fields for other calculations. Alternatively, you can generate formatted position-dependent field files (see Chapter 4-Loading/Saving Files) and read them in with the **Global BCs** or **Layer BCs Pages**.

If you want to bias a structure with an external field that is generated by magnets, set up the parameters for the internal grid of interest. Make the material properties of the grid those of the permanent magnet, especially the magnetization. For example, if the magnets lie at X = 0 and at X = X_{max} and are magnetized along +X, set m_x (left) = 1.0 and m_x (right) = 1.0. Click **Output File Name,** check the **Write File** box and name the file. Close the page and complete the initialization by starting the computation. Once LLG has computed the field tensor, the field from the boundary conditions will be computed and saved to the file. Exit LLG and restart your real problem; that is, the real sensor configuration. Use the **Boundary Conditions Page** to read in the fields generated by the magnets. Do not enter anything into the boundary conditions fields. Close the page and proceed. You will be able to visualize the fields using the **Boundary Conditions Field** viewer during the simulation phase.

In general, you can read in or save a formatted position-dependent magnetic field by clicking the **Input File Name** or **Output File Name** button.

Specifying Periodicity

LLG allows you to compute the properties of periodic structures. For three-dimensional structures, you can specify a structure to be periodic along any one or two of the three Cartesian directions. This is implemented with FFTs. Two-dimensional simulations can be periodic only in Y. The continuous boundary condition option allows you to model a bulk terminated surface, such as a domain wall, at the surface. In the LLG convention, continuous boundary conditions remove the magnetostatic charges from the bottom surfaces of the bottom row of sub-elements. Therefore, the magnetization appears continuous for all Y values below the bottom set of sub-elements. To implement this scheme, LLG uses the 2D-interface discretization scheme, as described earlier. (At present, the 2D Continuous feature is not active in v2 of LLG.)

IMPORTANT NOTE: For **2D Real FFT**s, the number of cells in a periodic direction ***MUST*** be a power of two.

- **Periodic along X**: Since the structure has wrap-around symmetry along X, the magnetostatic fields are periodic along X.
- **Periodic along Y and Z**: The structure has wrap-around symmetry along both Y and Z.

Setting a Continuous BC for 2D

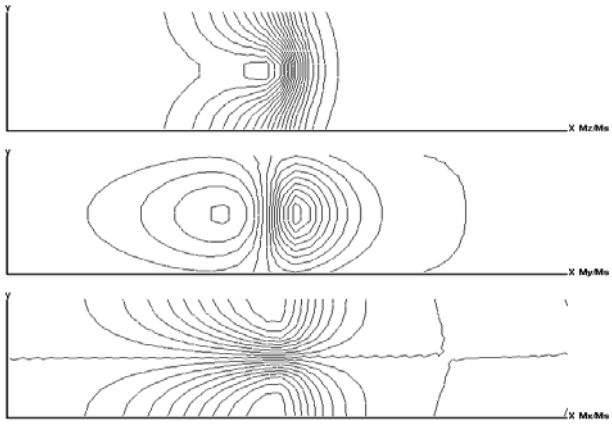
A continuous boundary condition can be set in Y for a 2D simulation, which removes the boundary along the bottom side (Y = min), allowing a semi-finite (terminated) solid to be simulated. (At present, the 2D Continuous feature is not active in v2 of LLG.)

Specifying Shaped Boundaries

Refer to page 119 for instructions on this feature.

Remember to click the **Accept Parameters** button if you want to keep your inputs.

Inputting Data into LLG-Notes



LLG provides you with a very simple way to enter comments about your problem. In addition to the problem title on the **Input Sheet-Main Page**, you have 10 additional ASCII fields for entering data in the **Input Sheet-Notes Page**, shown on the following page. By default, the date and time that the problem was loaded appear in the first field.

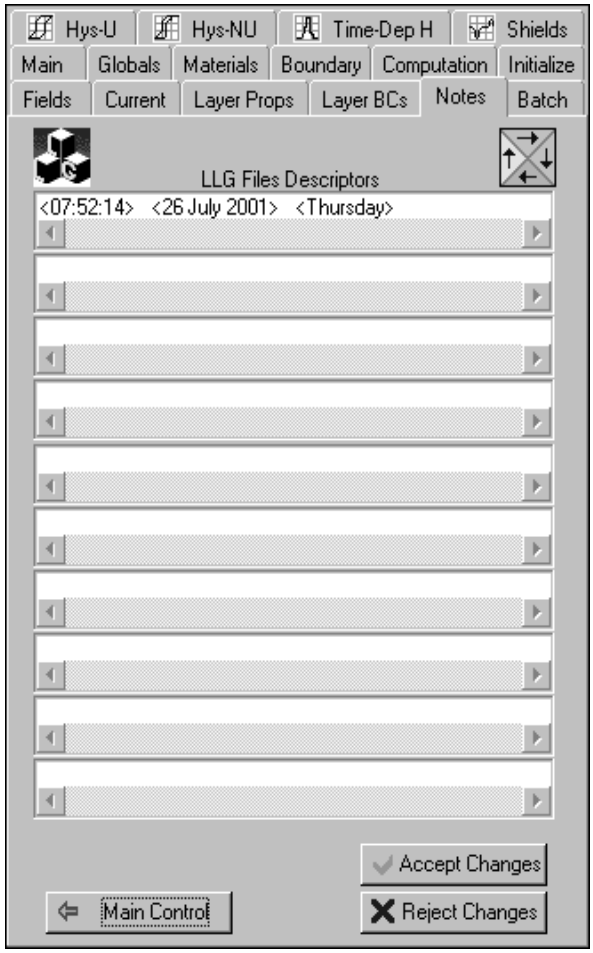
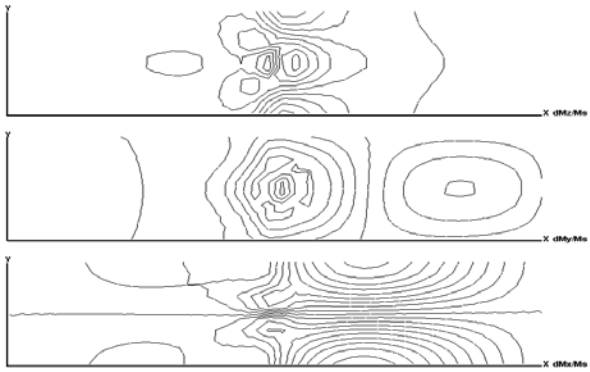


FIGURE 53. Input Data Sheet - Notes Page

CHAPTER 17

Inputting Data into LLG-Uniform Hysteresis Loop



The **LLG Input Sheet-Hys U Page** allows you to specify the field path along which to compute the hysteresis loop. The strength and orientation are specified by the three Cartesian field components. There are four principal methods for specifying the hysteresis field. All field profiles can be viewed in the OpenGL window either in **2D Field View** or **3D Field View**, with or without interpolating lines (toggle **With Lines**).

The **LLG Input Sheet-Hys U Page** allows you to specify loops with a uniform sampling of the magnetic field. This makes data entry easier. Internal to LLG, there is no difference between uniform or non-uniform or rotational hysteresis loops because LLG computes the field sequence and saves it in an internal array. To enter the field, you must specify the maximum field (LLG will start the loop at the positive maximum field, move to a negative maximum field, and then return to the positive maximum field) and the number of field points along a single branch. The negative maximum field point is sampled only once, which means that specifying 11 points to scan the field results in 21 total field points.

Data are summarized in the table below and the **Input Sheet-Hys U Page** is shown on the following page.

You can select either a uniform hysteresis loop (**Hys-U Page**), a non-uniform hysteresis loop (**Hys-NU Page**), a time dependent h-field (**Time-Dep H Page**) or a moving media problem (**Shields Page**). These are mutually exclusive; only one mode can be used for a given problem.

DESCRIPTION	VARIABLE	LIMITS
Loop Direction <x, y, z>	m_i	$-1.0 < m_i \leq 1.0$
$H_{x\text{-}hys}$	$H_{x\text{-}hys}$	$-10^{10} \leq H_{x\text{-}hys} \leq 10^{10}$
$H_{y\text{-}hys}$	$H_{y\text{-}hys}$	$-10^{10} \leq H_{y\text{-}hys} \leq 10^{10}$
$H_{z\text{-}hys}$	$H_{z\text{-}hys}$	$-10^{10} \leq H_{z\text{-}hys} \leq 10^{10}$
# Hysteresis Points	N_{hys}	$3 \leq N_{hys} \leq 16384$

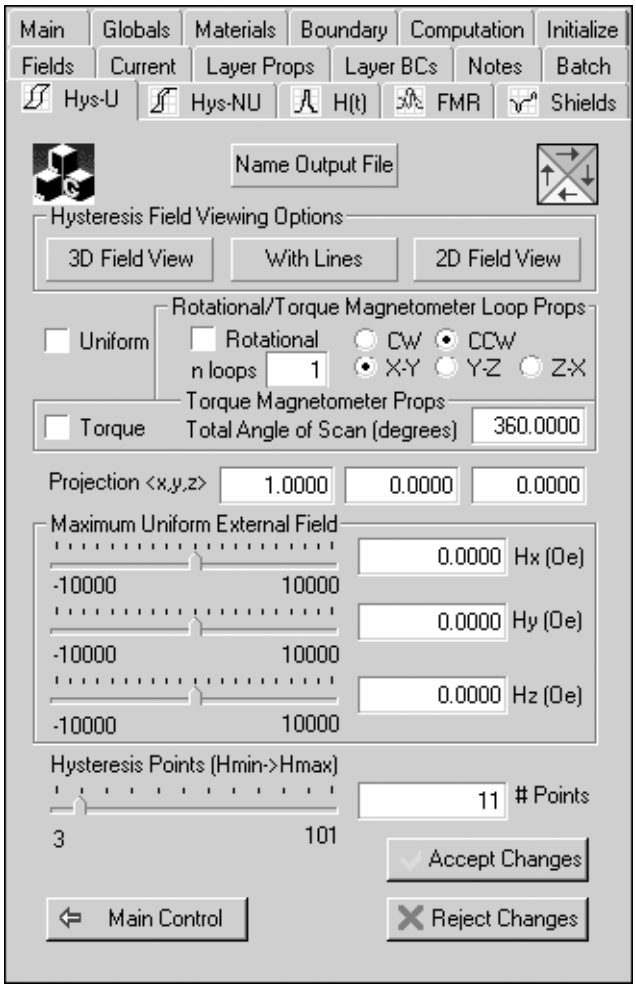


FIGURE 54. Input Data Sheet - Hysteresis: Uniform Page

SPECIFYING A UNIFORM LOOP

1. Check the **Uniform** box to calculate a uniform (field points are uniformly distributed) hysteresis loop. This is the simplest of all hysteresis options.
2. Use the slide bars or edit boxes to enter a **Maximum External Field**, which is the maximum field value for the hysteresis loop.
3. Enter the **# Points** with the slide bar or in the edit box. The distribution of field values will be visible in the OpenGL window. The number of field points in the whole loop will be 2n - 1, where n is the number defined in the edit box. The field values are distributed uniformly between the maximum and minimum (= negative of maximum vector) values of the field. If you want to determine zero field remanence, select an odd number of points along the branch for fields specified as $\pm H_{max}$.

In the following example, uniform hysteresis fields are shown in 2D and 3D with no interpolating lines. The field specifications are H_x = 2000 Oe, H_y = 1000 Oe and H_z = 2500 Oe, with the # **Points** = 21.The entire hysteresis loop will consist of 41 field points that are uniformly sampled.

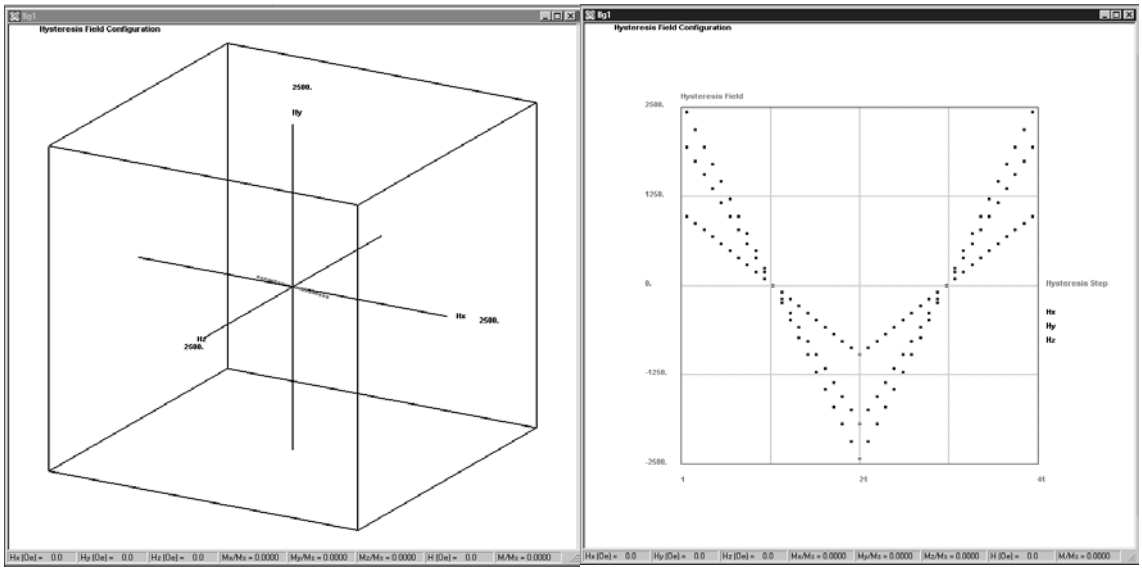


FIGURE 55. Hysteresis Loop Views for a Uniform-linear Hysteresis Loop

SPECIFYING A ROTATIONAL LOOP

You can perform rotational hysteresis loops by checking the **Uniform** and **Rotational** Hysteresis Loop boxes.

Specify a value of the field using the **Maximum External Field** bars or edit boxes. The vector direction of this field defines the angular coordinate of the first field point. You can specify the Cartesian plane in which you want the field rotation to be constrained by using the buttons provided (**X-Y**, **Y-Z**, or **Z-X**). The number of sample points is uniformly distributed around a circle. The magnitude of the field is

$$\left|\vec{H}\right| = \sqrt{H_x^2 + H_y^2 + H_z^2}$$

The hysteresis loop will be plotted on a polar diagram with the magnetization displayed radially for each field direction. An output file, *llg_hys, is created automatically. An example of a rotational hysteresis loop field follows. The field has been constrained to lie in the X-Z plane. The field values are H_x = 2000 Oe, H_y = 0 Oe and H_z = 1000 Oe, with the # **Points** = 21. The first field point lies at an angle of $\alpha = \tan^{-1}(1/2)$.

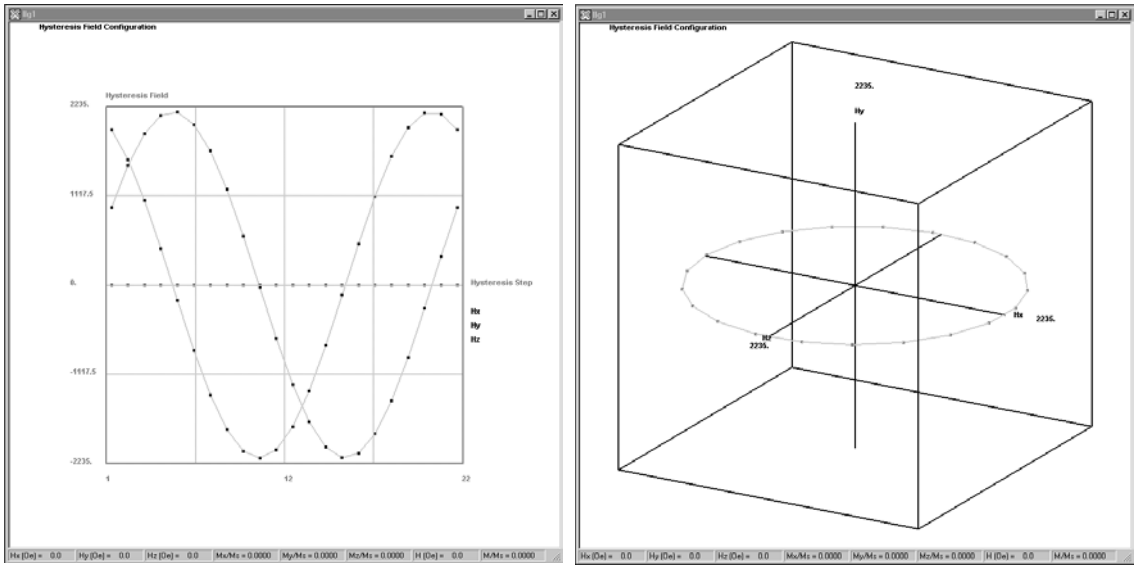


FIGURE 56. Hysteresis Loop Views for a Uniform-rotational Hysteresis Loop

SPECIFYING LOOP DIRECTION

The hysteresis loop is a plot of two scalar variables, H and M. The magnitude of H is given by the scanned field point dotted into some direction, and the value of the magnitude of M is that magnetization dotted into that same direction. The **Loop Direction** edit boxes are for specifying the x, y and z components of the direction cosine of which you want to obtain the hysteresis loop. By default, the x-direction is specified. Therefore, if you want you can scan the field along one direction and acquire a hysteresis loop projected along another. CW and CCW indicate the rotation sense of each loop.

SPECIFYING THE NUMBER OF LOOPS

The number of rotational loops may be entered. If the sample has not been trained, then at least 2 loops are required to determine the equilibrium rotational hysteresis loop. If the sample has already been trained, then a single loop will suffice.

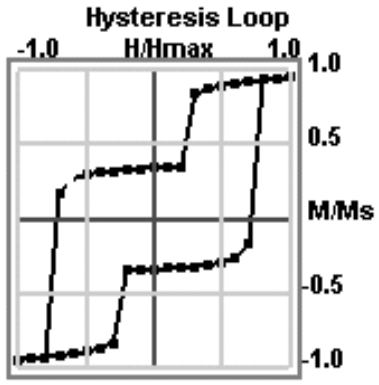
TORQUE MAGNETOMETRY

You must check uniform, rotational and torque check boxes (ALL THREE). You can specify the plane and the rotation sense as described above. When you check torque, LLG will make a single pass from the starting angle of field defined by Hx, Hy and Hz, pass through the defined angle in Nx increments and then return to the intial state. You can plot the loops as rotational or as a function of angle.

Please remember to click the **Accept Changes** button to record your changes to LLG's internal data structures.

CHAPTER 18

Inputting Data into LLG-Non-uniform Hysteresis Loop



SPECIFYING NON-UNIFORM SAMPLING HYSTERESIS LOOP

Often the magnetization does not undergo many changes while a hysteresis loop is being computed at field points away from the coercive field. It can be more economical, computationally, to sample field points coarsely in regions where the magnetization does not change quickly and on a fine grid near any switching fields. The non-uniform hysteresis field provides this flexibility; however, you must input more complicated data. The non-uniform hysteresis field component divides the field into sections. Each section is a linear interpolation of the field between its starting (**Limit 1**) and ending (**Limit 2**) field points. You can specify the number of points independently within each section. The first section contains both the starting and ending field points for that section, while subsequent sections join to the previous field section.

DESCRIPTION	VARIABLE	LIMITS
Loop Direction <x, y, z>	m_i	$-1.0 < m_i \leq 1.0$
Limit 1		
$H_{x\text{-}hys1}$	$H_{x\text{-}hys1}$	$-10^{10} \leq H_{x\text{-}hys1} \leq 10^{10}$
$H_{y\text{-}hys1}$	$H_{y\text{-}hys1}$	$-10^{10} \leq H_{y\text{-}hys1} \leq 10^{10}$
$H_{z\text{-}hys1}$	$H_{z\text{-}hys1}$	$-10^{10} \leq H_{z\text{-}hys1} \leq 10^{10}$
Limit 2		
$H_{x\text{-}hys2}$	$H_{x\text{-}hys2}$	$-10^{10} \leq H_{x\text{-}hys2} \leq 10^{10}$
$H_{y\text{-}hys2}$	$H_{y\text{-}hys2}$	$-10^{10} \leq H_{y\text{-}hys2} \leq 10^{10}$
$H_{z\text{-}hys2}$	$H_{z\text{-}hys2}$	$-10^{10} \leq H_{z\text{-}hys2} \leq 10^{10}$
# Hysteresis Points	N_{hys}	$3 \leq N_{hys} \leq 16384$
Field Section Specified	N_{sect}	$1 \leq N_{sect} \leq 16384$

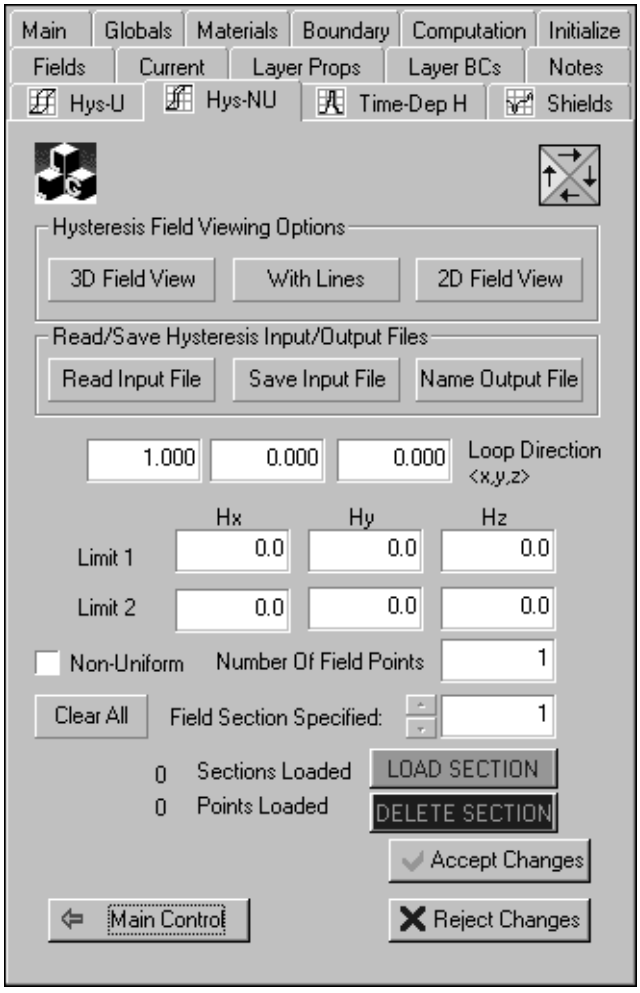


FIGURE 57. Input Data Sheet-Hysteresis: Non-uniform Page

You can select either a uniform hysteresis loop (**Hys-U Page**), a non-uniform hysteresis loop (**Hys-NU Page**), a time dependent h-field (**Time-Dep H Page**) or a moving media problem (**Shields Page**). These are mutually exclusive; only one mode can be used for a given problem.

SPECIFYING HYSTERESIS FIELD SECTIONS

To specify hysteresis field sections:

1. Check the **Non-Uniform** box to enable Non-Uniform hysteresis fields.
2. Use the arrows or the **Field Section Specified** edit box to indicate a field section, starting with the first.
3. Enter the starting (**Limit 1**) and ending (**Limit 2**) field values for the indicated Field Section into the edit fields.
4. Enter the **Number Of Field Points** for that section.

   While editing the Hysteresis Field Sections, you can click **DELETE SECTION** to remove field points from the hysteresis loop. To remove all the specified hysteresis sections, click the **Clear All** button.

THE NEXT THREE STEPS MUST BE FOLLOWED PRECISELY OR YOUR INPUT WILL NOT TAKE EFFECT

5. You ***MUST*** load the Field Section by clicking the **LOAD SECTION** button. Each section must be loaded, since the same controls are used both to examine and to modify the field values. Once you have loaded a section, it is automatically plotted in the OpenGL window.
6. ***Increment*** the **Field Section Specified** counter and enter the data for the next Field Section, following steps 2 through 5 above. ***REPEAT*** this process for each Field Section.
7. Once you have entered the data for ***ALL*** of the Field Sections, specify the **Loop Direction**. The hysteresis loop is a plot of two scalar variables, H and M. The magnitude of H is given by the scanned field point dotted into some direction, and the value of the magnitude of M is that magnetization dotted into that same direction. The **Loop Direction** edit fields are for specifying the x, y and z components of the direction cosine of which you want to obtain the hysteresis loop. By default, the x-direction is specified. Therefore, you can scan the field along one direction and acquire a hysteresis loop projected along another, if you choose.
8. Click **Accept Changes** when you have entered data for all of the sections or your data will not take effect.

Reading and Saving Hysteresis Input and Output Files

You can create a field file for generating hysteresis loops as an ASCII file using a text editor.

- These formatted files, *.llg_hysfield, can be read into the program with the **Read Input File** option. THE PROGRAM ALLOWS FOR NO MORE THAN 16384 FIELD POINTS. When reading a file, the program assumes that the field points are distributed non-uniformly. The field values are entered into the non-uniform edit field and are displayed in the OpenGL window. Such fields can be edited.
- When you create any type of uniform, uniform-rotational or non-uniform hysteresis field, the values of the fields can be output to a formatted ASCII file, *.llg_hysfield, by using the **Save Input File** button. You can generate a catalogue of field profiles that you commonly use.
- Use the **Name Output File** button if you want to rename the hysteresis data output default file, *.llg_hys. When you read in a file, the new data, once saved, become part of the *.llg_param file. Therefore, when you use the file in the future, you are not required to re-input the hysteresis field unless, of course, you change it.

EXAMPLE OF A NON-UNIFORM HYSTERESIS LOOP

The following example has seven field segments; the vectors are outlined in the table.

The first, fourth and seventh sections are coarsely sampled, while the second, third and sixth sections are sampled on a fine grid. You can use the arrow keys to display the contents of each section. To delete a section, use the **DELETE SECTION** button, the effects of which will be reflected in the OpenGL window.

The philosophy behind the non-uniform hysteresis field is that the field is specified on an arbitrary but connected path through field space. The hysteresis loop will be displayed with the component of the magnetization projected along the initial field direction. However, all the magnetizations and fields are written to the *.llg_hys file, so that you can display the data at a later time in any manner you wish.

		Limit 1			Limit 2		
Sec	# Pts	H_x	H_y	H_y	H_x	H_y	H_z
1	5	1000	0	0	500	0	0
2	21	500	0	0	0	0	0
3	21	0	0	0	-500	0	0
4	5	-500	0	0	-1000	0	0
5	5	-1000	0	0	-500	0	0
6	42	-500	0	0	500	0	0
7	5	500	0	0	1000	0	0

FIGURE 58. Non-uniform Hysteresis Loop Example

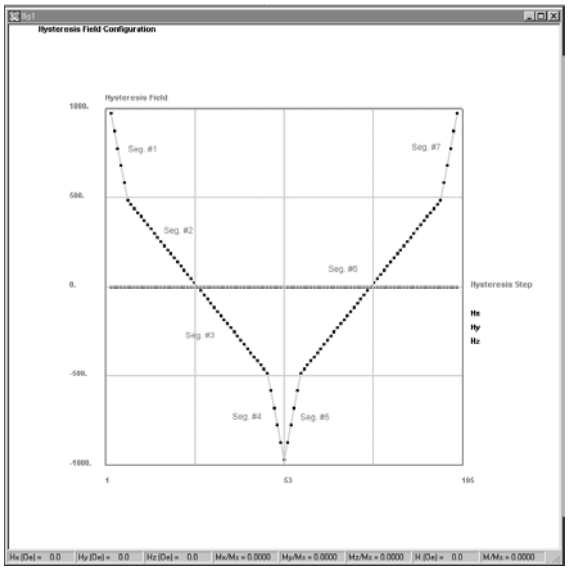
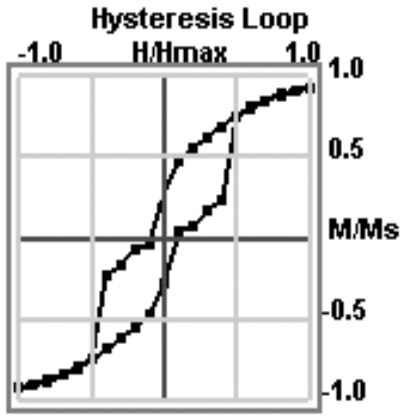


FIGURE 59. Hysteresis Loop View for a Non-uniform Hysteresis Loop

Please remember to click the **Accept Changes** button to record your changes to LLG's internal data structures.

CHAPTER 19

Inputting Data into LLG-H(t) and FMR Pages



SPECIFYING TIME DEPENDENT H FIELDS

The time dependent field component is divided into intervals. Each interval is a linear field interpolation between a starting (**T-1**) and an ending (**T-2**) time interval and an optional **ac** field component between a starting (**t1**) and an ending (**t2**) time interval. The first interval has the starting and ending field points, while subsequent sections join with the previous section. You can select either a uniform or a non-uniform hysteresis loop (**Hys-U** and **Hys-NU Pages**), a time dependent h-field (**Time-Dep H Page**) or a moving media problem (**Shields Page**). These are mutually exclusive.

DESCRIPTION	VARIABLE	LIMITS
Projection Direction <x, y, z>	m_i	$-1.0 < m_i \leq 1.0$
T-1 (ps)		
$H_{x\text{-}hys1}$	$H_{x\text{-}hys1}$	$-10^{10} \leq H_{x\text{-}hys1} \leq 10^{10}$
$H_{y\text{-}hys1}$	$H_{y\text{-}hys1}$	$-10^{10} \leq H_{y\text{-}hys1} \leq 10^{10}$
$H_{z\text{-}hys1}$	$H_{z\text{-}hys1}$	$-10^{10} \leq H_{z\text{-}hys1} \leq 10^{10}$
T-2 (ps)		
$H_{x\text{-}hys2}$	$H_{x\text{-}hys2}$	$-10^{10} \leq H_{x\text{-}hys2} \leq 10^{10}$
$H_{y\text{-}hys2}$	$H_{y\text{-}hys2}$	$-10^{10} \leq H_{y\text{-}hys2} \leq 10^{10}$
$H_{z\text{-}hys2}$	$H_{z\text{-}hys2}$	$-10^{10} \leq H_{z\text{-}hys2} \leq 10^{10}$
Time Interval (Steps)	Steps	$1 \leq \text{Steps} \leq 16384$
Time Interval Specified	T_{sect}	$1 \leq T_{sect} \leq 16384$
ac Fields $h_x\ h_y\ h_z$	$h_x\ h_y\ h_z$	$-10^{10} \leq h_x\ h_y\ h_z \leq 10^{10}$
ac Time $t_1\ t_2$	$t_1\ t_2$	$1 \leq t_1\ t_2 \leq 16384$
ac Frequency and Phase	b c	$0 \leq b\ c \leq 10^{10}$
Time(ps)Step	T	$0.01 \leq T \leq 10^6$

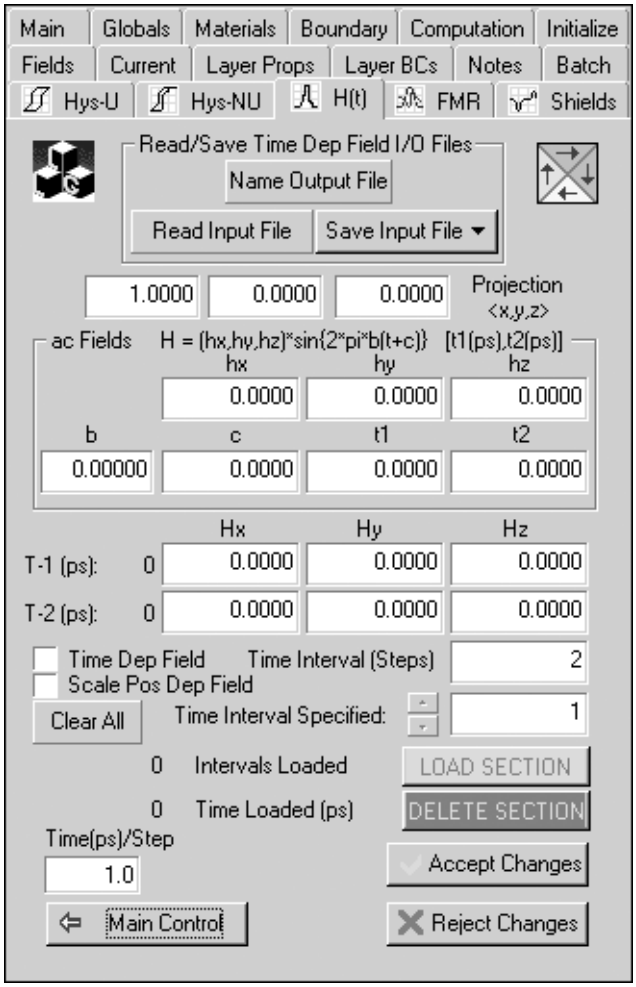


FIGURE 60. Input Data Sheet - Time-Dependent H Page

SPECIFYING PROJECTION DIRECTION

The hysteresis loop is a plot of two scalar variables, H and M. The magnitude of H is given by the scanned field point dotted into some direction, and the value of the magnitude of M is that magnetization dotted into that same direction. The **Projection Dir** edit fields are for specifying the x, y and z components of the direction cosine of which you want to obtain the hysteresis loop. By default, the x-direction is specified. Therefore, you can scan the field along one direction and acquire a hysteresis loop projected along another if you choose.

SPECIFYING A TIME DEPENDENT FIELD

To specify a time dependent field:

1. You ***MUST*** first check the **Time Dep Field** box to enable time-dependent fields.
2. Specify the time interval in the **Time Interval Specified** edit box, starting with the first.
3. Set the specified interval's starting and stopping fields in the **T-1 (ps)** and/or **T-2 (ps)** edit boxes.
4. Specify the **Time Interval (Steps)**. Each **Time Interval Specified** must have a corresponding **Time Interval (Steps).**
5. Specify the **Time(ps)/Step**, which ***MUST*** be the same for each interval.

THE NEXT THREE STEPS MUST BE FOLLOWED PRECISELY OR YOUR INPUT WILL NOT TAKE EFFECT

6. You ***MUST*** load the field section by clicking the **LOAD SECTION** button. Each section must be loaded, since the same controls are used both to examine and to modify the field values.
7. ***Increment*** the **Time Interval Specified** counter and enter the data for the next field sector, following steps 2 through 6.
8. Click **Accept Changes** when you have entered data for all of the sections.

While editing the time-dependent field sections, click **DELETE SECTION** to remove field points from the hysteresis loop. Remove all the specified **Time Intervals** by clicking the **Clear All** button.

SPECIFYING SINUSOIDAL FIELDS

You may optionally enter a **Sinusoidal** field that will be superimposed upon the fixed interval fields that are specified with the **Time-Dep H Page**. The sinusoidal fields allow you optionally to investigate FMR type excitations.

- You must enter the value of the ac field components into the $\mathbf{h_x}$, $\mathbf{h_y}$ and $\mathbf{h_z}$ edit boxes. You may only specify a single **ac** field.
- You can enter the starting and stopping times, $\mathbf{t_1}$ and $\mathbf{t_2}$, in ps. This allows you to time shift the ac component of the field.
- You can enter the frequency, **b** (1/ps), and the shift, **c** (ps), to fix the **ac** field frequency and the phase shift of the excitation wave.

READING AND SAVING TIME DEPENDENT FIELD INPUT AND OUTPUT FILES

You can create a field file for generating hysteresis loops as an ASCII file using a text editor.

- These formatted files, *.llg_hysfield, can be read into the program with the **Read Input File** option. THE PROGRAM ALLOWS FOR NO MORE THAN 16384 FIELD POINTS. When reading a file, the program assumes that the field points are distributed non-uniformly. The field values are entered into the non-uniform edit field and displayed in the OpenGL window. Such fields can be edited.
- When you create any type of uniform, uniform-rotational or non-uniform hysteresis field, the values of the fields can be output to a formatted ASCII file, *.llg_hysfield, by using the **Save Input File** button. You can generate a catalogue of field profiles that you commonly use.
- Use the **Name Output File** button if you want to rename the hysteresis data output default file, *.llg_hys. When you read in a file, the new data, once saved, become part of the *.llg_param file. Therefore, when you use the file in the future, you are not required to re-input the hysteresis field unless, of course, you change it.

Please remember to click the **Accept Changes** button to record your changes to LLG's internal data structures.

SPECIFYING TIME VARYING POSITION DEPENDENT FIELDS

By checking the Scale Pos Dep Field check box, LLG will (after computing the coupling matrices) prompt you for a position dependent input field file. The time and position dependent field that results uses the input from this Page to scale the data as follow:

$H_x(x,y,x,t) = H_x pos(x,y,z)*H_x(t)$ in dialog

$H_y(x,y,x,t) = H_y pos(x,y,z)*H_y(t)$ in dialog

$H_z(x,y,x,t) = H_z pos(x,y,z)*H_z(t)$ in dialog

In this way you can simulate write head field time dependences on media. You cannot simultaneously scan a uniform field in time and a position dependent field in time. However, you may use the MRAM fields as independent time varying uniform fields (Current Page) at any time during a simulation.

FMR AND DYNAMIC SUSEPTIBILITY

You may choose between computing the FMR loop (scanning H for a fixed frequency) or a dynamic susceptibility loop (scanning frequency for a fixed external field). To activate FMR you must check the **Do FMR/Suseptibility** check box. You can select between FMR and Dynamic suseptibility by clicking on the appropriate (**FMR** or **Chi**) button. You specify the number and range of the DC field points, an ac field magnitude (in H_x for now) and a frequency in the FMR case, or a DC field, and ac field and the number and range of frequency in the susceptibility case. Since LLG computes FMR loops in time, you should be sure to uncheck the convergence and iteration boxes in the computation page so not to exit prematurely. Also leave the t-2(ns) check box in the Compution page unchecked. LLG will store the frequency dependent field in an array, and accumulate the magnetization vector at each time step. Once one period of oscillation is complete, LLG will compute the real and imaginary part of the susceptibility at the frequency of excitation (LLG measures the peak in the ac excitation and finds the time shift relative to the peak in the ac field). You set an exit criteria at the bottom the of FMR page as the largest fractional change in the susceptibility and the minimum number of cycles. Since the field ramp may only produce a small perturbation to the oscillating magnetization, I typically choose 3 or 4 periods as the minimum. Also, please note that there are only 1000 points in the susceptibility arrays so 1/(f x time-step) < 1000. LLG will warn you if you exceed the memory limit. Internally, LLG computes the entire matrix of the susceptibility. However, for now, I have constrained the field to vary in x and I have output only the real and imaginary parts of χ_{xx}, in other works m_x/h_x.

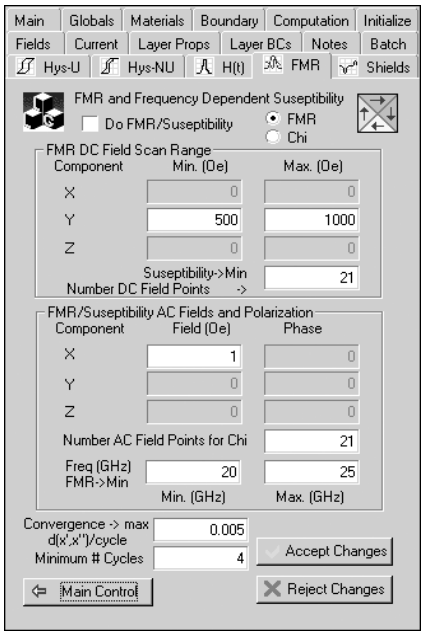
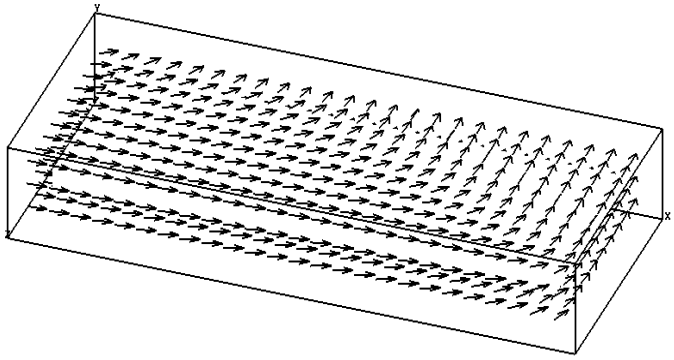


FIGURE 61. FMR Page

CHAPTER 20

Inputting Data into LLG-Shields



You can specify the presence and position of finite permeability field shields, as well as specify the media used to excite a sensor. You can use shields for any problem under study. You can select either a uniform hysteresis loop (**Hys-U Page**), a non-uniform hysteresis loop (**Hys-NU Page**), a time dependent h-field (**Time-Dep H Page**) or a moving media problem (**Shields Page**). These are mutually exclusive; only one mode can be used for a given problem.

SPECIFYING SHIELD ATTRIBUTES

For any LLG simulation, you can select shields that are parallel to X-Y planes only and that are separated from the object under study in Z.

- Activate either one or two shields by checking the **Min** and/or **Max** boxes.
- In the **Distance to Shield (nm)** edit boxes below **Min (Below) On/Off** and **Max (Above) On/Off**, enter the distance in nanometers from the bottom or top of the shield to the magnetic material of the shield's inner (towards simulation volume) surface.
- These vacuum gap distances are measured from the top and/or bottom of the magnetic material to the surface of the Mu metal shield. Internal to LLG, the shields are replaced with 3D image charges to screen current and sensor magnetization. For shielding the fields due to external fields and media fields, the finite extent of the shields in the transverse direction must be specified. In the **Shield Edge** edit boxes, you must enter the distance in nanometers from the edge of the magnetic material to the edge of the shield in the transverse direction.
- Enter the relative permeability of the shields in the **Mu/Mu0** edit box, which accounts for the image charges due to the current.

> **IMPORTANT NOTE**: Since shields register true 3D coordinates for image charges, when you run a problem with **2D Real FFTs**, LLG can provide the appropriate handling of the images for the magnetic material in the Simulation Volume itself. In other computation modes, the images of the magnetic dipoles of the sensor in the shields are not included in the calculation. This differs from LLG v1, where the computation was done approximately in inverse space. LLG allows you to run the calculation in any mode, but the only one that supports the images of the charges in the shields is the **2D Real FFT Method**. However, current images and boundary condition charges are included for all cases.

- Check the **Shield Loop**s box to shield micromagnetic elements from external fields during hysteresis loop calculations. This is useful when computing the performance of MR head sensors.

Consult the Sample Problems to study how a particular implementation will affect the outcome of your problem.

RESPONSE TO MODEL (ATAN) MEDIA CHARGE

To compute cross-track response, you can specify the properties of a magnetic medium to be moved in proximity to a sensor. The media has, by default, an atan transition.

Specifying the Media

Check the **Use/Move Media** box. Then, specify the following:

- The position of the **Center X, Y, Z(nm)** of the transition.
- The axis that the media transition is **parallel to** (X,Y or Z).
- The media $\mathbf{M_s}$ (saturation magnetization).
- The media thickness **T(nm)**.
- The transition width **W(nm)**.
- The transition length **L(nm)**.

When the media is scanned in front of a sensor, you must specify the following:

- The direction in which to vary the position (**X, Y** or **Z**).
- The minimum position **Min (nm)**.
- The maximum position **Max (nm).**
- The number of **Steps** used to complete the movement.

Please remember to click the **Accept Changes** button to record your changes to LLG's internal data structures.

DESCRIPTION	VARIABLE	LIMITS
Shield Attributes (for both shield above and/or shield below in appropriate column)		
Distance to Shields	D_s	$0.0 \leq D_s \leq 10^6$
Shield Thickness (nm)	T_s	$0.0 \leq T_s \leq 10^6$
Distance 0 -> Shield Edge (X)	$D_{x\text{-left}}$	$0.0 \leq D_{x\text{-left}} \leq 10^6$
Distance Nx -> Shield Edge (X)	$D_{x\text{-right}}$	$0.0 \leq D_{x\text{-right}} \leq 10^6$
Distance 0 -> Shield Edge (Y)	$D_{y\text{-front}}$	$0.0 \leq D_{y\text{-front}} \leq 10^6$
Distance Ny -> Shield Edge (Y)	$D_{y\text{-back}}$	$-0.0 \leq D_{y\text{-back}} \leq 10^6$
Permeability Mu/Mu0	μ	$0 \leq \mu \leq 10^6$
Response to Model (atan) Media Charge		
II To	X,Y or Z	X,Y or Z
X(nm)	X	$-10^6 \leq X \leq 10^6$
Y(nm)	Y	$-10^6 \leq Y \leq 10^6$
Z(nm)	Z	$-10^6 \leq Z \leq 10^6$
Scan Media Min (nm)	Min	$-10^6 \leq Min \leq 10^6$
Scan Media Max (nm)	Max	$-10^6 \leq Max \leq 10^6$
Scan Media Steps	N	$0 \leq N \leq 10^6$
Media M_s	M_{sm}	$0 \leq M_{sm} \leq 10^6$
Media Thickness T(nm)	T_m	$0 \leq T_m \leq 10^6$
Transition Width W(nm)	W_m	$0 \leq W_m \leq 10^6$
Transition Length L(nm)	L_m	$0 \leq L_m \leq 10^6$

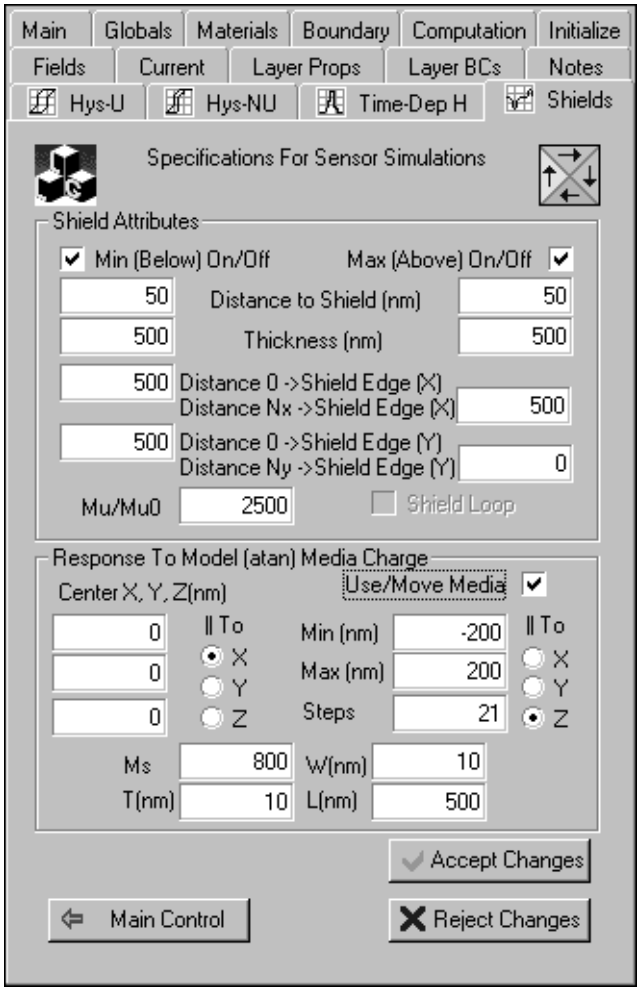
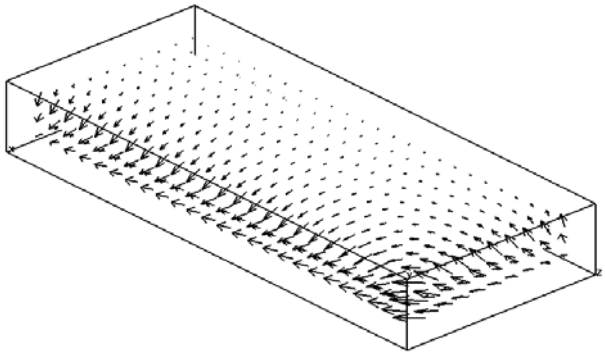


FIGURE 62. Input Data Sheet - Shields Page

CHAPTER 21

Inputting Data into LLG-Mask Editor



The **Input Sheet - Mask Editor Page** is where you shape the magnetic system by turning individual cells on and off. Mask files are binary files that contain sequential integer fields with ones and zeros. There are two masks. The first mask contains information about which sub-elements have non-zero magnetization. The second mask determines which sub-elements will be used when the hysteresis or MR loop is visualized.

ACCESSING MASKS

To access masks in LLG, memory must be committed. This means that the size of the problem can no longer be changed. To commit memory, check the **Commit Size** box on the **Main Page**. Once memory has been committed, you can access the **Mask Editor Page** by clicking the **Masks** button on the Main Page. Once you have initiated the Mask Editor, shown on the following page, a new Mask View is loaded into the OGL window.

DEFINING A MASK SHAPE

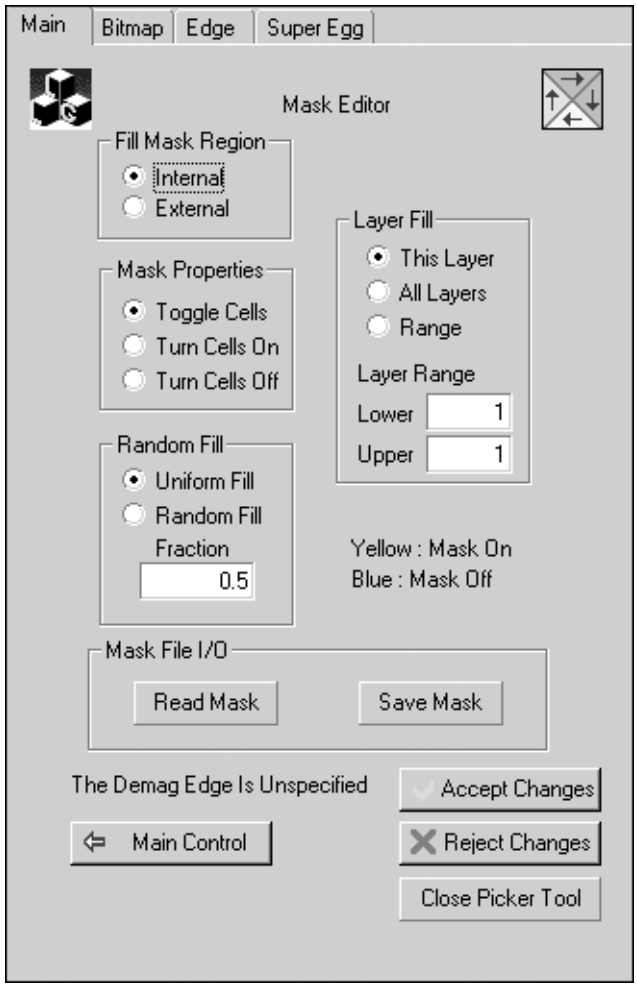
You define the mask using the mouse.

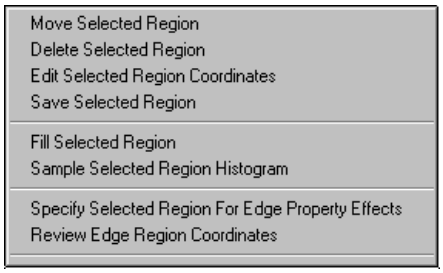
1. In the **Graphics Control**, set **X**, **Y** or **Z** to establish the orientation (projection) of the layer or layers that you want to work with. This activates the drawing tool and the **Drawing Tool Bar** will be visible. The default color of the drawing pen is **Red**. You can change the color to Black, Green or Blue. You can adjust the size of the pen as well.

FIGURE 63. Mask Editor Tool Bar

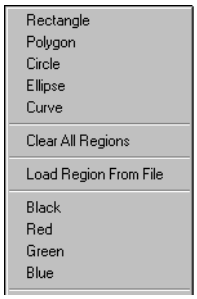
2. ***Choose*** the type of shape that you wish to draw. The default is a rectangle.
3. Use the mouse to draw the shape. Its position in nm will be output to the OGL window frame at bottom right.
   - For the **rectangle, circle** and **ellipse**, left click with the mouse to choose the starting position and continue to hold down the mouse. Dragging the mouse outlines the shape under construction. Release the mouse button at the final point to mark out the shape.
   - For the **polygon**, you must left click for each point that you wish to define, and double click to close the polygon.
   - The **arbitrary line** allows you to draw a wavy line and enclose any shape that you choose to define.
   - Click the **CLR** button to clear all defined shapes.

MASK EDITOR SHEET - MAIN PAGE





When you use any of the Mask Editor Pages, right click on the active graphic for the options above. These features can be performed on existing graphics.



When you use any of the Mask Editor Pages, right click on the background of the window for the options above, which are for creating or loading new graphics.

FIGURE 64. Mask Editor Sheet - Main Page

There are two options and **Mask Editor Pages** for specifying masks. The first option is to specify a mask through the **Main Page**, using the instructions that follow; the second option is to import a bitmap, jpeg or targa file through the **Bitmap Page** (see page 142).

Specifying Mask Properties (Option one)

One you have defined the appropriate shape, you can define how to act on the points either interior or exterior to that shape.

- You can **Fill the Mask Region** either **Internal**ly or **External**ly. In each case, the action of changing the cell types will occur either within or outside of the defined shape.
- You can either **Toggle Cells** (i.e., the logical NOT operation), **Turn Cells On** (On) or **Turn Cells Off** (Off), under **Mask Properties**.
- Instead of turning cells on or off completely (**Uniform Fill**) within the defined region, you might want to change the properties of the cells randomly (**Random Fill**).
- A univariate random number generator is used to turn off cells as a function of location with a probability of a **Fraction** of those cells being specified. For example, since random numbers are generated between 0 and 1, a Fraction of 0.5 makes it equally probable to turn cells on or off. If you choose a fraction of 0.75, on average 3/4 of the cells will be turned off (or on depending upon the Mask Properties option selected) and so on.
- You can select how the fill factors are generated throughout the layers using the **Layer Fill** options. Since the view is constrained to be one projected into two dimensions, you must specify the actions that are to take place in the third projected dimension. Your choices are to act only on **This Layer** (the one visualized and adjusted through the Graphics Control), **All Layers** or on a **Range** of layers as specified by the **Lower** and **Upper** edit fields. Here, layers are actually the discretized sub-element count, not the actual material layer number.

Color Coding

Yellow indicates active cells and blue indicates inactive cells.

Determining if the Demagnetization Edge is Unspecified

To compute the properties of shaped boundaries (see page 87), you must specify one boundary to define the shaped edges. LLG states on the bottom of the menu whether or not this shaped edge has been defined.

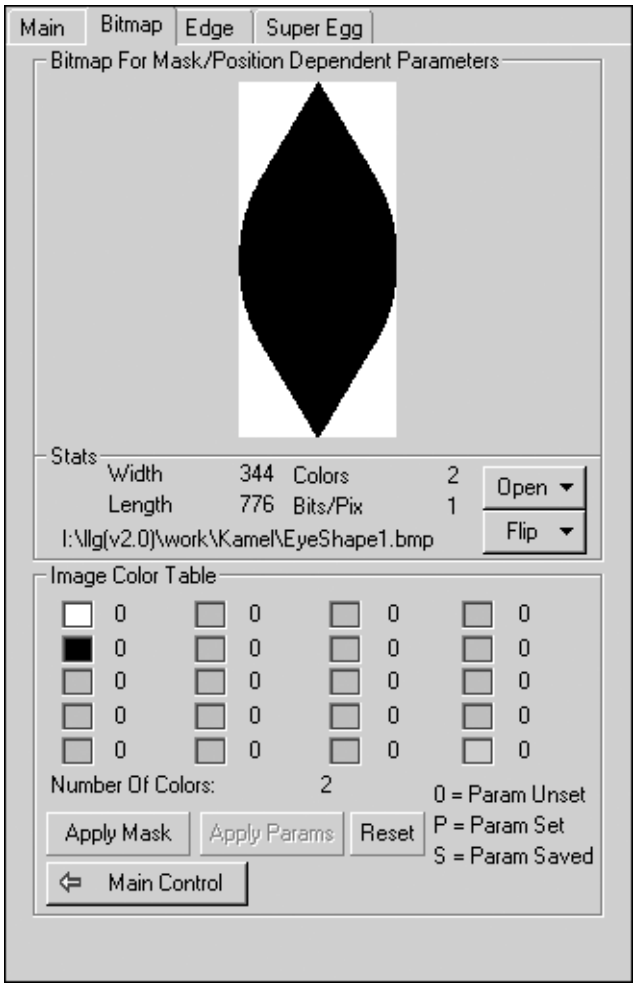
Reading and Saving Mask Files

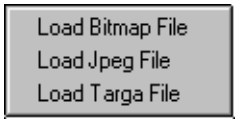
Mask files are binary files that contain sequential integer fields with ones and zeros. You can load an *.llg_mask file using the **Read Mask** button. If the requested mask does not have the same dimensions as your problem, it will be interpolated onto the existing grid. This is a binary or digital interpolation. You can save a mask file at any time with the **Save Mask** button.

Closing the Mask Sheet

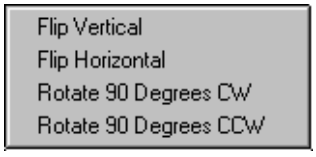
Once you have completed your problem specification, it is highly suggested that you save your parameters file using the **Save Mask** button. Then, you must click **Accept Changes** if you wish your changes to be recorded. Finally, you must click **Close Picker Tool** to close the **Mask Editor**.

MASK EDITOR SHEET - BITMAP PAGE





*Click the **Open** button to load the files in the menu above.*



*Click the **Flip** button for the options in the menu above.*

FIGURE 65. Mask Editor Sheet - Bitmap Page

SPECIFYING MASK PROPERTIES (OPTION TWO)

The second option for specifying mask properties is to import a bitmap, jpeg or targa file that you have created with a separate graphics application. ***IMPORTANT NOTE***: LLG recognizes and applies ***ONLY BLACK*** as the color of the mask; so, the mask region of your graphic ***MUST BE BLACK*** in the RGB sense: (0,0,0).

1. Specify which layers you want to mask on the **Main Mask Editor Page** and whether you want to toggle (turn on or turn off) the region (internal or external).
2. Load an image file by clicking the **Open** button and selecting the file type from the options. An image of the file will be painted in the window on the **Bitmap Page**. The spatial extent of the image is scaled to match the size of the projection of your structure.
3. To flip and rotate the image, click the **Flip** button and select the desired option.
4. Click the **Apply Mask** button to visualize your changes in the graphics window.

This **Bitmap Page** also appears in the **Position Dependent Parameter Sheet**; the **Image Color Table** and **Apply Params** features apply only to that Sheet. The only feature relevant to making a mask is specifying the black portion of the image.

MASK EDITOR SHEET - EDGE PAGE

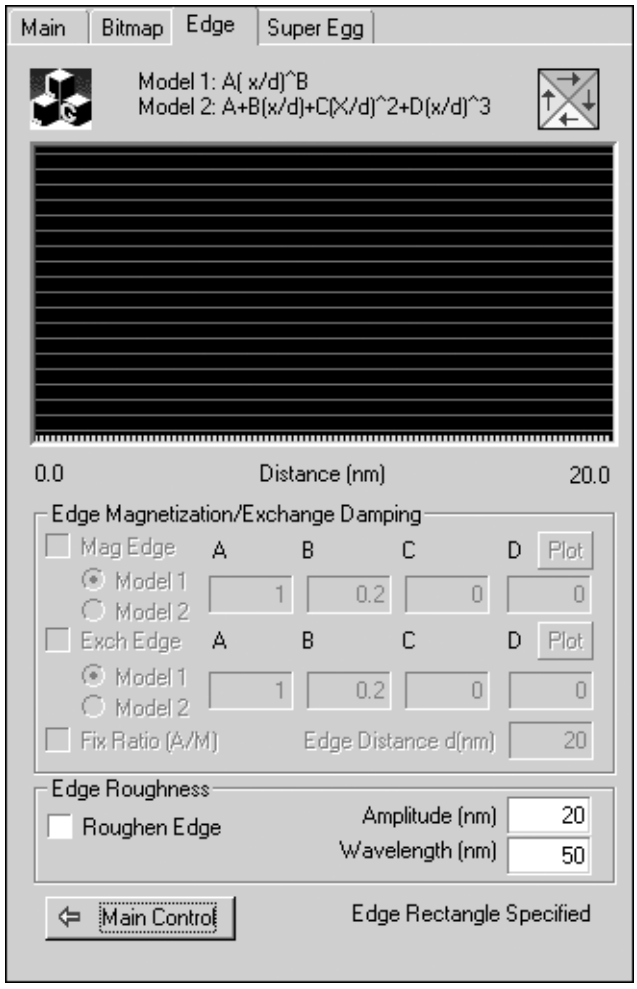


FIGURE 66. Mask Editor Sheet - Edge Page

You can specify periodic **Edge Roughness** on the **Edge Page**.

1. Specify which layers you want to mask on the **Main Mask Editor Page** and whether you want to toggle (turn on or turn off) the region (internal or external).
2. Draw a region with the Drawing Tool (see page 139).
3. Right click on the graphic and select **Specify Selected Region for Edge Property Effects** from the pop-up menu.
4. Check the **Roughen Edge** box and specify the **Amplitude** and **Wavelength** of the roughness in nm in the edit boxes.
5. Right click on the graphic and select **Fill Selected Region** from the pop-up menu.

This Page also appears in the Position Dependent Parameter Sheet; the **Edge Magnetization/Exchange Damping** features apply only to that Sheet.

MASK EDITOR SHEET - SUPER EGG

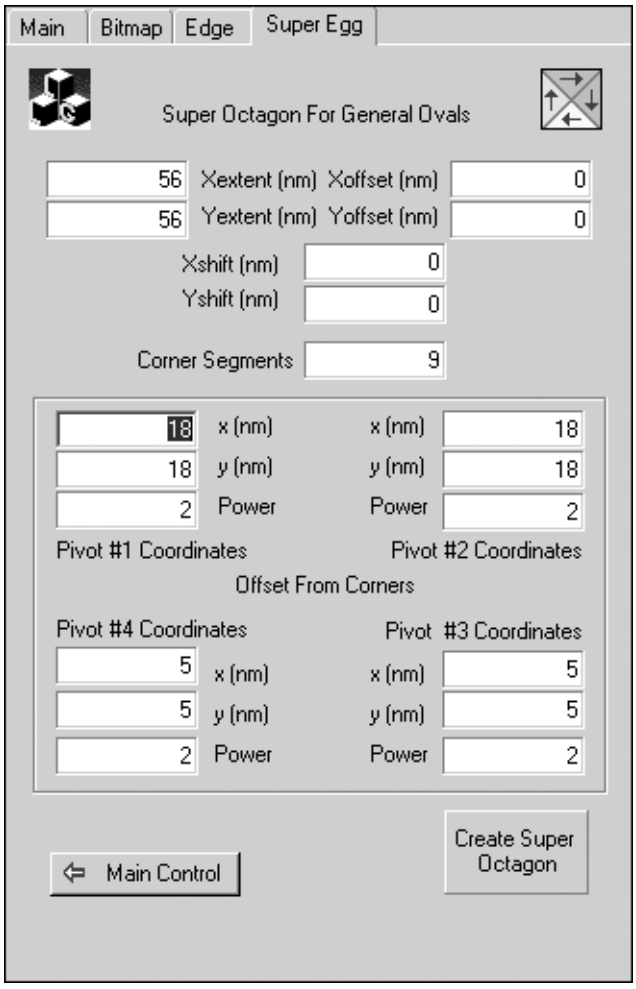


FIGURE 67. Mask Editor Sheet - Super Egg

The super-egg (or superoctagon) has eight parameters, length, width, thickness, four corner parameters and an exponent for the curvature of the four corners. The corners are quadrants of a superoval given by $(x/x_0)^n + (y/y_0)^n = 1$. This addition to LLG was prompted by Prof. Tony Arrott and Dr. Terry Templeton who routinely use the super-egg to define stable modes for MRAM switching. The super-egg encompasses all shapes from pointed corners to flat edges depend-

ing upon the size (and sign) of the exponent. A series of super egg examples shown below. The maximum number of vertices that you can enter in the polygon mode and super-egg mode has been expanded to 1000.

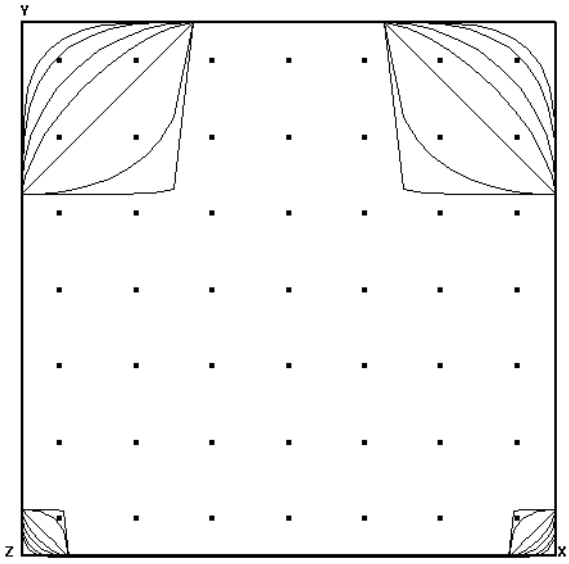


FIGURE 68. Super Egg.

EDITING THE GRAPHIC COORDINATES

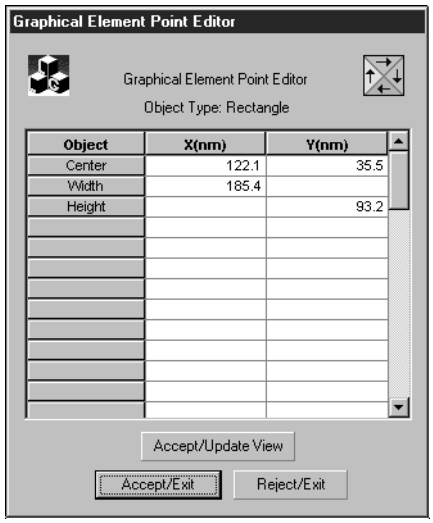


FIGURE 69. Mask Editor Sheet - Graphical Element Point Editor

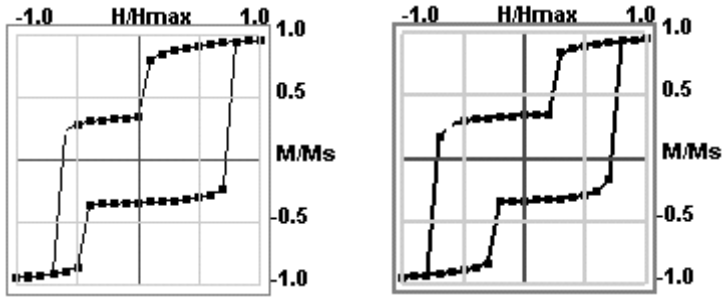
Sometimes the specification of your graphic requires a precision that cannot be achieved with the mouse. In this case:

1. Approximate the graphic with the drawing tool.
2. Right click on the graphic and select **Edit Selected Region Coordinates** from the pop-up menu. The menu above will appear with the coordinates of the graphic in the edit fields.
3. Edit the coordinates to create the desired graphic dimensions.

You can update the view before accepting the changes by clicking the **Accept/Update View** button.

CHAPTER 22

Inputting Data into LLG-Position Dependent Parameters



The I**nput Sheet-Position Dependent Parameters Page** is for locally altering the parameters in the magnetic system.

However***, BEFORE*** you can even access and enter data into the Position Dependent Parameter Pages, you ***MUST*** have first defined the global parameters and committed the memory according to the sequence outlined below.

.

INPUT PREREQUISITES FOR POSITION DEPENDENT PARAMETERS

1. Enter **Global** data.
2. Check the **Layers** box under Structure Properties on the Main Page.
3. Enter layer data on the **Layer Props Page** (see page 90).

   IMPORTANT NOTE FOR 1-LAYER POSITION-DEPENDENT STRUCTURES*:** Even if your structure has 1 layer, to apply position-dependent parameters you ***MUST first define the structure as 1-layer on the Layer Props Page. In this case, the layer thickness (defined on the Layer Props Page) and the total thickness of the structure (defined on the Main Page) are equal.
4. Check the **PosDep** box (not the button) under **Structure Properties** on the Main Page.
5. Check the **Commit Size** box on the Main Page, which allows you access to the Position Dependent Parameter Sheet. ***Once you commit memory, the size of the problem can not be changed***.
6. Click the **PosDep** button on the Main Page, which activates the **Position Dependent Parameter Editor**, shown on page 150, and loads a new Mask View into the OGL window.

BASIS STEPS FOR ESTABLISHING POSITION-DEPENDENT PARAMETERS

For ***EACH*** area to which you want to apply position-dependent parameters, you must complete following steps. Technically, steps 1 through 3 can be completed in any order.

1. Define the area of interest with the drawing tool.
2. Select a color for the area of interest from the **Params Page** to distinguish it graphically and to be sure that the parameters take effect. (This is an optional but highly recommended step.)
3. Specify the position dependent parameters that you want to apply to the defined area of interest.
4. Apply the parameters, including the selected color, to the defined area of interest.

DEFINING AN AREA OF INTEREST WITH THE DRAWING TOOL

To define an area of interest:

1. Click the **OGL Props** tab; then click the **Orient** tab in the **Graphics Control** at the bottom.
   - Set the **Position** of **X**, **Y** or **Z** to establish the orientation (projection) of the layer or layers.
   - If your structure has more than one layer, indicate the layer that you want to work with the **Slice** bar, which will reflect the number of layers in your structure. If you established layer colors in the **Layer Props Page**, they will be evident as you scroll through the layers.

   (**NOTE**: This control is synchronized with the **Layer Fill - This Layer** option in the **Main Page**. You can apply additional **Fill** and **Mask** properties on the **Main Page**).

   This activates the **Drawing Tool Bar** at the top. The default color of the drawing pen is **Red**. You can change the color to Black, Green or Blue. You can adjust the size of the pen as well.

FIGURE 70. Position Dependent Parameter Editor Tool Bar

2. Select the shape that you wish to draw. The default is a rectangle.
3. Use the mouse to draw the shape. As you move the mouse, its position in nm will be output to the OGL window frame at bottom right.
   - For the **rectangle, circle** and **ellipse**, left click with the mouse to choose the starting position and continue to hold down the mouse. Dragging the mouse outlines the shape under construction. Release the mouse button at the final point to mark out the shape.
   - **NOTE**: For the **polygon**, you must left click for each point that you wish to define, and double click to close the polygon.
   - The **arbitrary line** allows you to draw a wavy line and enclose any shape that you choose to define.
   - Click the **CLR** button to clear all defined shapes.

SELECTING A COLOR FOR THE AREA OF INTEREST

You can use color coding to distinguish the region of position-dependent parameters and as an indication that your input takes effect.

1. Click the **Params** tab. Select a color from the **drop-down color box**, which is at the bottom just to the left of the **Clear** button.
2. Check the box beside the drop-down color box to indicate that you want the selected color to take effect.
3. Click the **OGL Props** tab in the **Graphic Control** at the bottom; then, click the **Modes** tab. Then, you ***MUST*** check the **CO** (color) box for your color selection to appear in the OGL screen. (The CO box is enabled during the Input Phase of LLG only when position-dependent files are being defined.)

Inputting Position-dependent Parameters for the Area of Interest

Follow the Input Strategy outlined in the chart below. Refer to the rest of this chapter for specific instructions for each of the **Position Dependent Parameter Pages**.

Applying the Parameters and the Selected Color to the Area of Interest

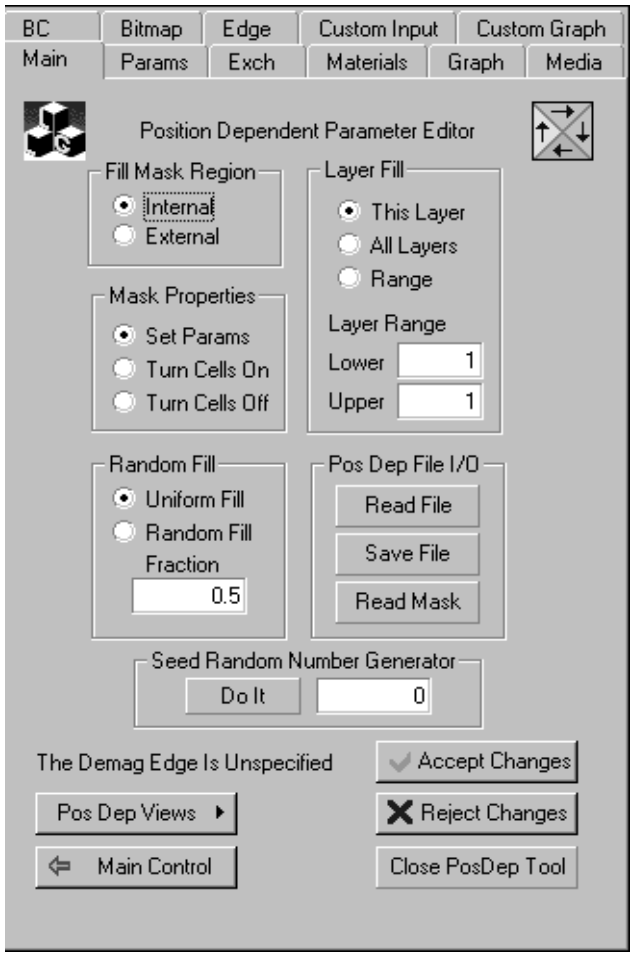
Once you have defined a shape and entered the position-dependent parameters for the area of interest, right click inside the shape you have drawn and select, **Fill Region with Parameters.** Your selected color should appear.

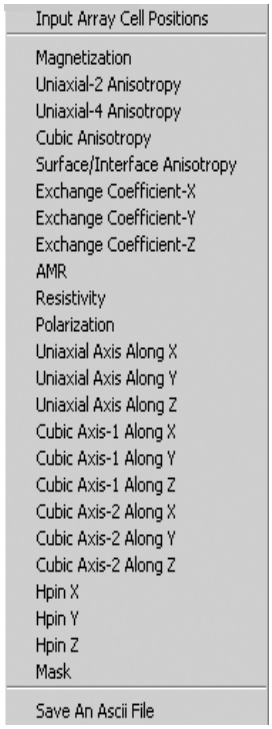
INPUT STRATEGY FOR POSITION-DEPENDENT PARAMETERS

1. Define a mask shape with the **Drawing Tool** (see page 148).
2. Select a color for the shape. (Optional but highly recommended.)
3. Select **Internal** or **External Fill Mask Region**.
4. Select **Mask Properties**.
5. Select **Uniform** or **Random Fill**.
6. If desired, **Seed Random Number Generator** by entering an integer seed and clicking **Do It**.
7. Specify the **Layer Fill**.
8. Specify parameters through the **Params Page**.
9. Specify the edge **Exchange** through the **Exch Page**.
10. Specify media properties through the **Media Page**.
11. Specify boundary conditions through the **BC Page**.
12. Right click on the region in the OGL window and select **Fill Region with Parameters**.

    NOTE: Parameters will be cleared. To view the color changes, check the **CO** box below in the **OGL Props Sheet - Modes Page** in the **Graphic Control**. Use the **Selector Page** in the Graphics Control to test individual cells (see page 71). On the **Graph Page**, you can also select a region and reapply the distribution to view.
13. Repeat steps 1-12 for each area to which you want to apply position-dependent parameters.

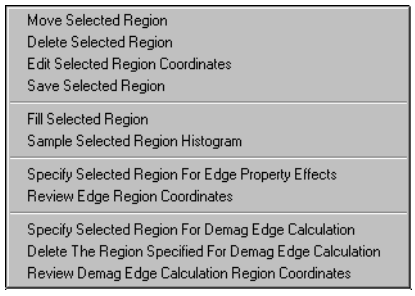
POSITION DEPENDENT PARAMETER SHEET - MAIN PAGE



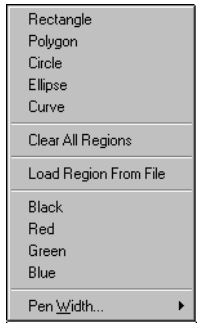


*Click the **Pos Dep Views** button to activate the pop-up menu above. Each parameter can be visualized, including those specified in the **Parameter** and **Exchange Pages**. The **Input Cell Position** is required for editing; so, always return to this view to edit the cells or to specify a shape.*

FIGURE 71. Position Dependent Parameters Sheet - Main Page


Move Selected Region
Delete Selected Region
Edit Selected Region Coordinates
Save Selected Region
Fill Selected Region
Sample Selected Region Histogram
Specify Selected Region For Edge Property Effects
Review Edge Region Coordinates
Specify Selected Region For Demag Edge Calculation
Delete The Region Specified For Demag Edge Calculation
Review Demag Edge Calculation Region Coordinates

In Mask Editor, right click on the active graphic for these options, which can be performed on existing graphics.



In Mask Editor, right click on the background of the window for these options, which are for creating or loading new graphics.

FIGURE 72. Position Dependent Parameters Sheet - Pop-up Menus

Once you have defined an area of interest, you can apply additional fill and mask characteristics to the area through the **Position Dependent Parameters Sheet-Main Page**.

Specifying Fill Mask Region

You can **Fill Mask Region Internal**ly or **External**ly, which changes the cell types either inside or outside of the shape.

Specifying Mask Properties and Random Fill

You can set the **Mask Properties** with the following options.

- You can select **Set Params**, which is the default and applies the specified parameters to the defined region.
- You can **Turn Cells On** or **Turn Cells Off** completely within the defined region.
- Additionally, you can apply the specified properties either uniformly or randomly to the defined region by selecting **Uniform Fill** or **Random Fill**.

  A univariate random number generator is used to **Turn Cells Off** or **Turn Cells On** as a function of location, with a probability that a **Fraction** of those cells will be on or off. You must enter a number between 0 and 1 into the **Fraction** edit field. For example, 0.5 (the default) means that it is equally probable that the cells will be turned on or off. If you enter 0.75 into the **Fraction** edit field, then on average 3/4 of the cells will be turned off or on.

  If you want to be able to repeat a **Random Fill** in the future, use the **Seed the Random Number Generator** feature**.** For example, enter an integer permutation of the date and time into the edit field and use that same integer the next time in a different region or in a different simulation, the properties will be applied in the ***SAME*** random order.

  To activate that seed, click the **Do It** button.

Specifying Layer Fill

You can select how the fill parameters are applied throughout the layers using the **Layer Fill** options. Since the view is constrained to be one projected into two dimensions, you must specify the actions that are to take place in the third projected dimension.

- You can apply parameters to **This Layer** only. You specify the layer with the **Graphics Control** at the bottom. Click the **OGL Props** tab; then, click the **Orient** tab. Set the layer with the **Slice** bar, which will reflect the number of layers in your structure. (If you established layer colors in the **Layer Props Page**, they will be evident as you scroll through the layers.)
- You can apply parameters to **All Layers**, which automatically loads the layer range of your structure into the edit fields. This means the defined area will drill through all layers of the structure.
- You can apply parameters to a **Range** of layers, which means the defined area will drill through a specified **Range** of layers. Enter the range in the **Lower** and **Upper Layer Range** edit fields. In this sense, layers are actually the discretized sub-element count, not the actual layer number.

You must specify the properties themselves that apply the defined area in the **Params**, **Exch**ange, **Materials**, **Media** and **BC Pages**, which follow.

Reading and Saving Position-dependent Files

Position dependent files are binary files that contain a huge amount of sequential double-precision fields. You can load an *.llg_position file using the **Read File** button. If the requested file does not have the same dimensions as your problem, it will be rejected. You can save a position file at any time with the **Save File** button. Click the **Read Mask** button to import a mask file.

Determining if the Demagnetization Edge is Unspecified

To compute the properties of shaped boundaries (see page 87), you must specify one boundary to define the shaped edges. LLG states on the bottom of the menu whether or not this shaped edge has been defined.

POSITION DEPENDENT PARAMETERS SHEET - PARAMS PAGE

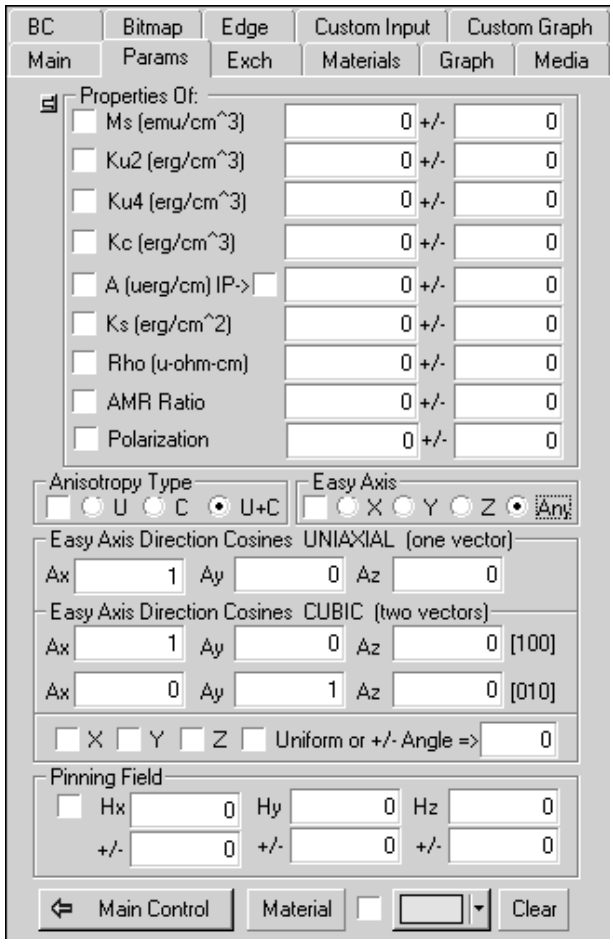


FIGURE 73. Position Dependent Parameters Sheet - Parameters Page

This page is for specifying position-dependent material properties as outlined in Chapter 7-Globals or Chapter 14-Layer Properties. The one difference here is that you must check the properties that you want to change. If a box is ***CHECKED***, then that property ***WILL BE CHANGED;*** if a box is ***UNCHECKED***, then that property ***WILL REMAIN AS SPECIFIED***.

- Check the **IP** box adjacent to the exchange parameter, which indicates that you want to modify only the in-plane component of the exchange parameter.
- The **+/-** edit fields are for inputting a gaussian random variable to the properties that you specify. For example, if you choose a saturation magnetization of 800 and use +/- 100, the generated magnetization will vary cell by cell within the region of interest, with the magnetization given by 800 +/- 100 gaussian random variable.
- Click the **Clear** button to reinitialize your input configuration.
- Click the **Material** button to access the database for selecting parameters for the materials edit fields.
- Use the drop-down color box to select a color to apply to the region. You ***MUST*** also check the **CO** box in the **Graphics Control** for the color to appear in the OGL window once you have applied the properties to the region. (Click the **OGL Props** tab; then, click the **Modes** tab to access this feature.)

POSITION DEPENDENT PARAMETERS SHEET - BOUNDARY REGION EXCHANGE PAGE

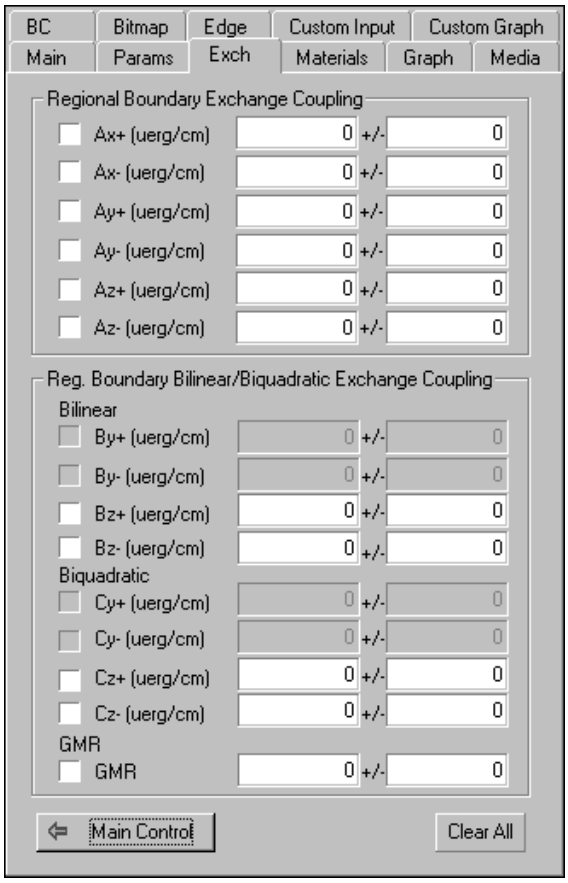


FIGURE 74. Position Dependent Parameters Sheet - Exchange Page

This page is for inputting position-dependent boundary exchange parameters, such as for exchange isolating a small region in the center of a structure that is defined by grain boundaries where Tantalum might have segregated, leading to exchange isolation.

There are six sides to each cell and, in general, there are x+, x-, y+, y-, z+ and z- projecting faces for any Cartesian structure. Here, the pluses (**+**) and minuses (**-**) refer to sides whose outward facing normals are directed along the positive or negative axes. ***Actions supplied through this page apply ONLY to the cells that BOUND the region. Only those properties that you check are applied.*** All others remain unchanged.

- **A** is intercell exchange.
- **B** is interlayer Bilinear Exchange across non-magnetic spacers.
- **C** is interlayer Biquadratic Exchange across non-magnetic spacers.
- **GMR** specifies the layer-dependent GMR ratio for the layer region inside the defined structure.
- The **+/-** edit fields at right are for inputting a gaussian random portion to the specified parameter. For example, if you choose A_x+ of 1.05 and use +/- 0.20, the generated exchange stiffness along x+ will vary cell by cell within the region of interest, with the exchange stiffness given by 1.05 +/- 0.20 gaussian random variable.

POSITION DEPENDENT PARAMETERS SHEET - MATERIALS PAGE

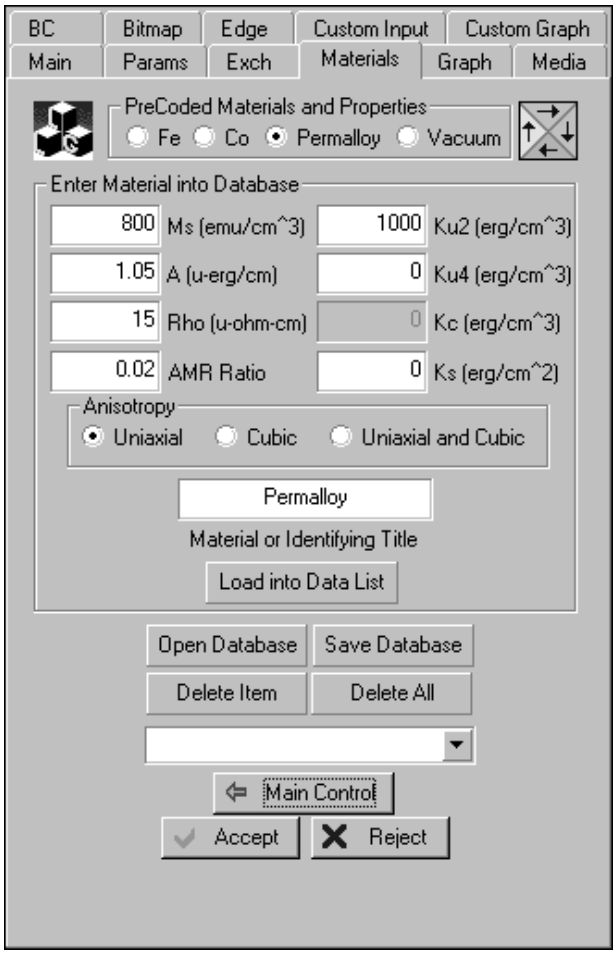


FIGURE 75. Position Dependent Parameters Sheet - Materials Page

The properties of this page are identical to those outlined in Chapter 8-Materials.

POSITION DEPENDENT PARAMETERS SHEET - GRAPH PAGE

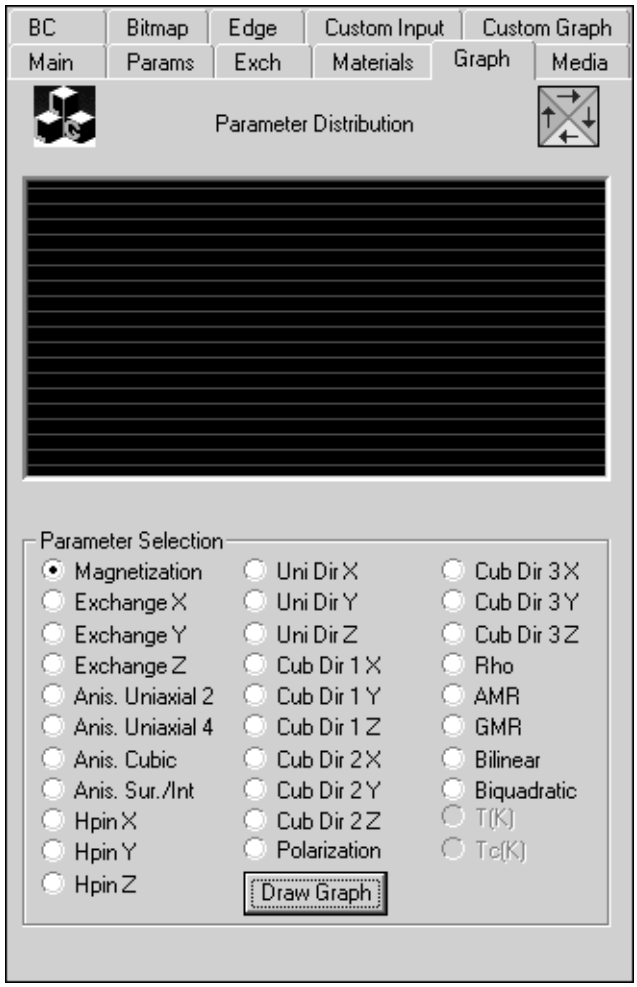


FIGURE 76. Position Dependent Parameters Sheet - Graph Page

Once you have specified parameters for a problem, you can analyze those properties through the **Graph Page**.

1. Define a region of interest (see page 148).
2. Right click on the region and select **Distribution Resample** (generate a histogram of the data for viewing).
3. Then, click the **Draw Graph** button to illustrate a histogram of your **Parameter Selection**.

Be sure that you have specified the desired properties. In the sample in the menu above, a saturation magnetization of 800 +/- 100 was selected. The graph illustrates the gaussian distributed random variables centered about 800 with a σ of 100.

POSITION DEPENDENT PARAMETERS SHEET - MEDIA PAGE

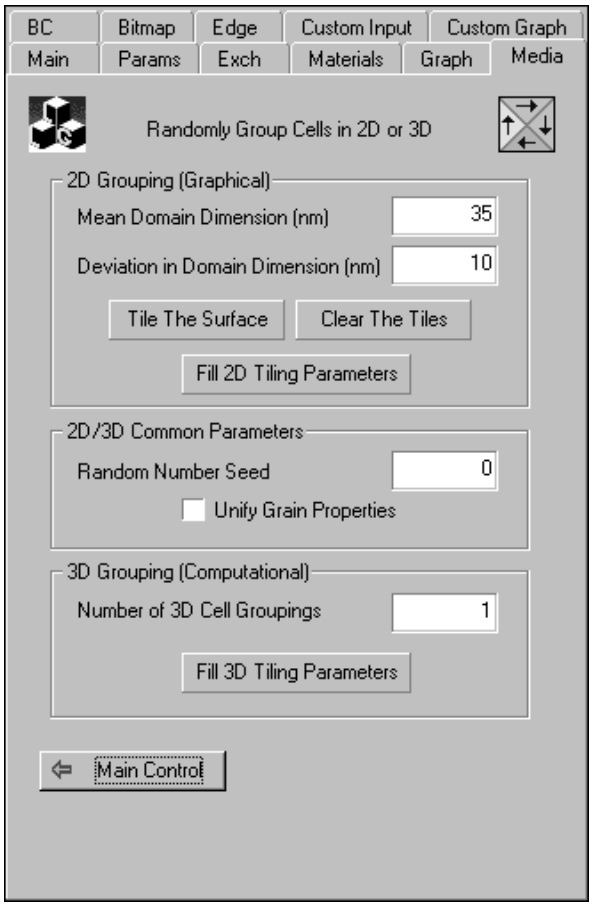


FIGURE 77. Position Dependent Parameters Sheet - Media Page

The **Media Page** is a simple tool to assist you in generating parameter properties for regions that are common in magnetic media, where there are many grains with separate, yet consistent, magnetic properties. Groupings can be done in two or three dimensions. For two-dimensional groupings, set the **Mean Domain Dimension** and the **Deviation in Domain Dimension**. For three-dimensional groupings, specify the **Number of 3D Cell Groupings**. In the 3D case, LLG will randomly choose n points within the cell volume. Then, cells of a given group are so assigned to ensure that each cell is closest to a given point. This is a simplistic implementation of three-dimension Voronoi cells.

1. Enter the parameters in the **Main**, **Params** and **Exch Pages**. Define suitable grain structures through the **Media Page**.
2. Enter the **Mean Domain Dimension (nm)** in the edit field. This sets the length scale for defining the domains (i.e. grains).
3. Specify the **Deviation in Domain Dimension (nm)** in the edit field, i.e., the degree to which the size of the grains is random.
4. Since the randomness is set using a random number generator, you can select a **Random Number Seed** to recreate a given tile distribution.
5. Check the **Unify Grain Properties** box if you want each tiled region (grain) to have identical properties. When this is selected, the parameters random number generator randomizes only by tile, not by cell.

6. Once the data is specified, click **Tile The Surface** to see how your space can be filled.
7. If you are satisfied with the distribution, click **Fill Parameters** to set the parameters; otherwise, click **Clear The Tiles** and try again. A simple tiling example follows. Refer to Sample Problem 20-Media for an example.

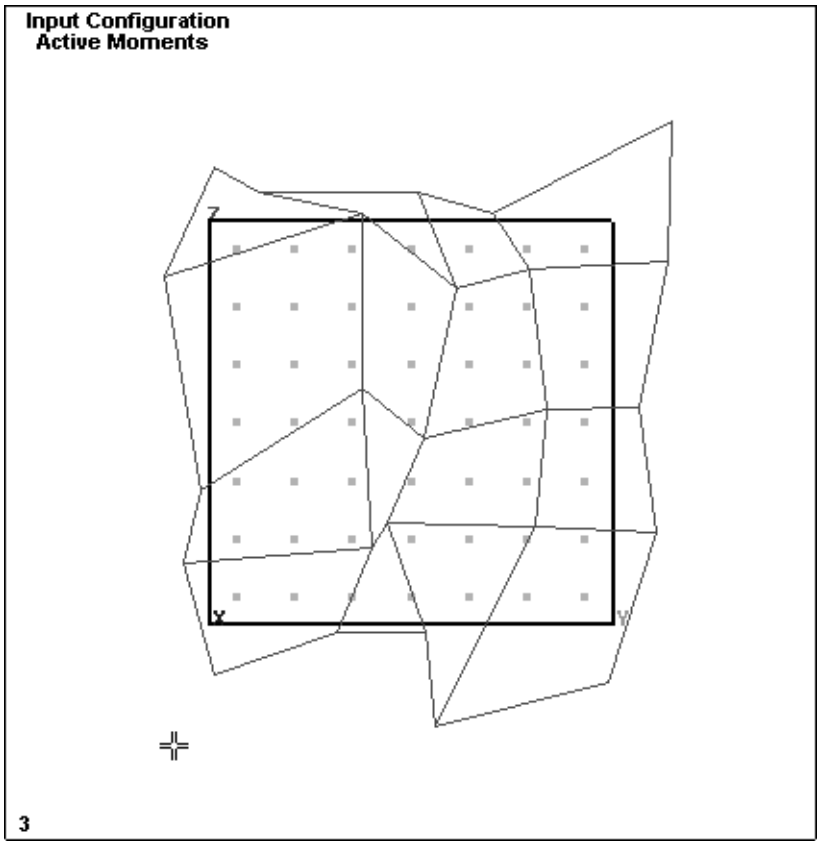
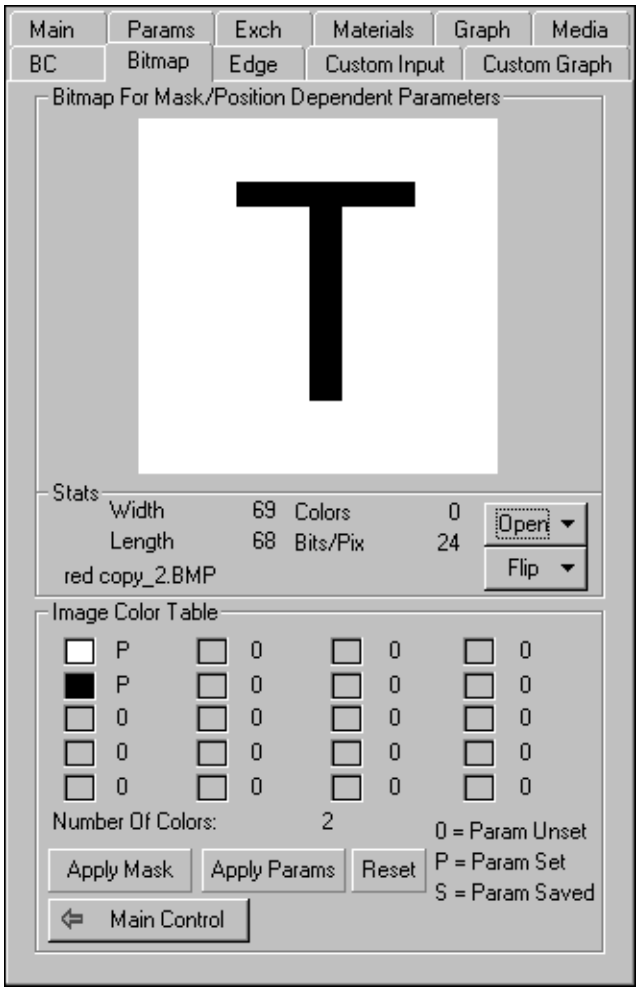
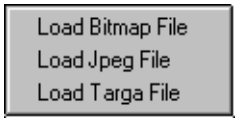


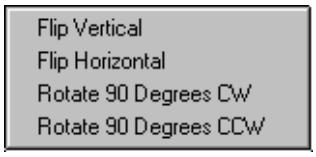
FIGURE 78. Position Dependent Parameters Sheet - Simple Tiling Example

POSITION DEPENDENT PARAMETERS SHEET - BITMAP PAGE

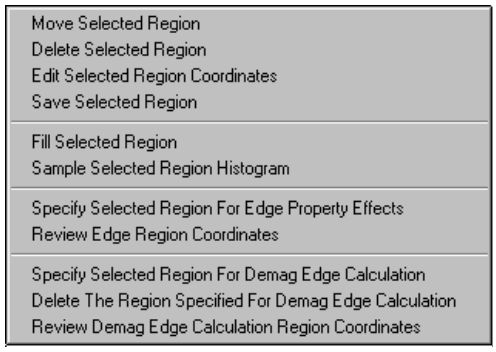




*Click the **Open** button to load files listed in the menu above.*



*Click the **Flip** button for the options listed in the menu above.*


Move Selected Region
Delete Selected Region
Edit Selected Region Coordinates
Save Selected Region
Fill Selected Region
Sample Selected Region Histogram
Specify Selected Region For Edge Property Effects
Review Edge Region Coordinates
Specify Selected Region For Demag Edge Calculation
Delete The Region Specified For Demag Edge Calculation
Review Demag Edge Calculation Region Coordinates

*Click one of the color boxes in the **Image Color Table** for the options listed in the menu above.*

FIGURE 79. Position Dependent Parameters Sheet - Bitmap Page

Specifying a Mask or Properties with an Imported Image

A second option for specifying mask properties is to import a bitmap, jpeg or targa file that you have created with a separate graphics application.

> **IMPORTANT NOTE:** LLG recognizes and applies ***ONLY BLACK*** as the color of the mask; so, the mask region of your graphic ***MUST BE BLACK*** in the RGB sense: (0,0,0).

- Specify which layers you want to mask on the **Position Dependent Parameter Main Page** (page 151) and whether you want to turn on or turn off the region internally or externally.
- Load an image file by clicking the **Open** button and selecting the file type from the options. An image of the file will be painted in the window on the **Bitmap Page**. The spatial extent of the image is scaled to match the size of the projection of your structure.
- To flip and rotate the image, click the **Flip** button and select the desired option.
- Click the **Apply Mask** button to visualize your changes in the graphics window.

Defining Position Dependent Parameters with an Imported Color Map

Instead of using LLG's drawing tool, you can import an image (that you have created with a separate graphics application) with up to 20 regions of color. LLG uses the image as a map for identifying mask or position dependent parameter regions, with each region identified by a color. LLG reads the image pixel by pixel, starting with the first pixel in the upper left, and generates a record of up to 20 colors from the image. This allows you to specify up to 20 parameter sets for an imported image.

Only the properties from the **Main**, **Params** and **Exchange Pages** of the **Position Dependent Parameter Sheet** apply to the regions of color. When you read in a new image, LLG clears the internal data arrays that record the parameters associated with a given color.

1. Import the graphic by clicking the **Open** button. LLG records the colors of the graphic in the **Image Color Table.**
2. Specify which layers you want to work with on the **Position Dependent Parameter Main Page** (page 151) and whether you want to toggle (turn on or turn off) the region (internal or external).
3. Enter the data into the **Main**, **Params** and **Exchange Pages** of the **Position Dependent Sheet**.
4. Left click the color box whose parameters you wish to set and select **Save Parameters From Pages to LLG Arrays** from the pop-up menu. LLG places the **Parameter Set Indicator**, **P**, next to the color in the **Image Color Table**.
5. Save the color parameters to a file: click the color box and select **Save A Single Color Parameter Set To A File** from the pop-up menu.
6. Repeat this for each color that you wish to change.
7. Once you have specified the entire array of parameter values, save the entire parameter history to a file by clicking the color box and selecting **Save All Color Params to a File** from the pop-up menu. You can reuse this file at a later time; you can apply the parameters from the file to a new image with the ***same number of color regions*** by selecting **Load All Colors' Parameters From a File** from the pop-up menu.
8. Click a color box and select either **Fill This Color's** or **Fill All Colors' Position Dependent Parameters** to visualize the parameters in the graphics window.

Click the **Reset** button if you want to clear the image, colors and all of the parameters from **Bitmap Page**.

POSITION DEPENDENT PARAMETERS SHEET - EDGE PAGE

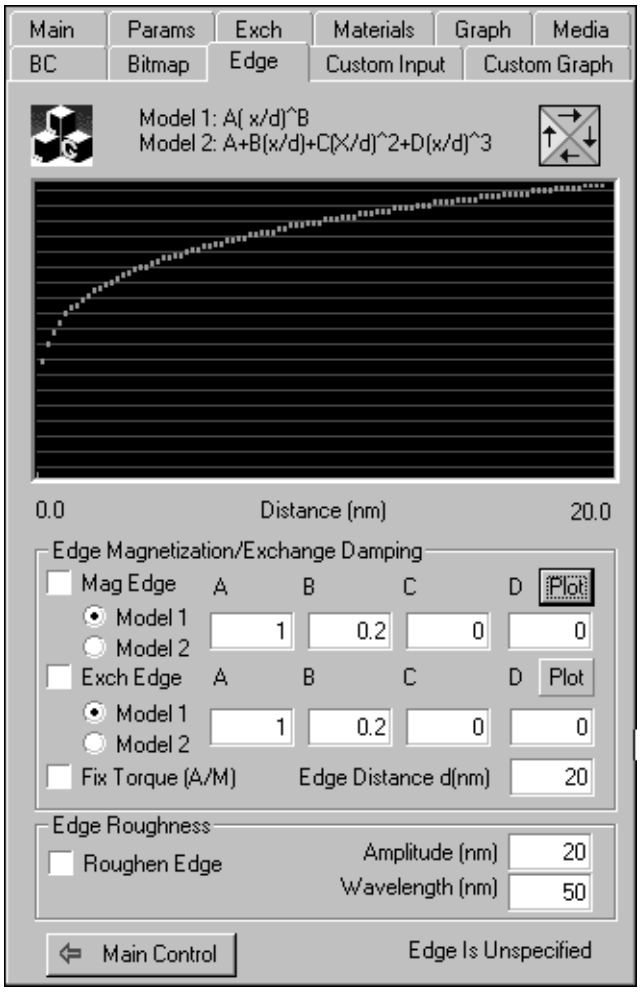


FIGURE 80. Position Dependent Parameters Sheet - Edge Page

Specifying Edge Magnetization and Exchange Damping

The two formulas for specifying Edge Magnetization and Exchange Damping appear at the top of the Edge Page.

1. Specify which layers you want to work with on the **Position Dependent Parameter Main Page** (page 151) and whether you want to toggle fill parameters and layers.
2. To scale the position-dependent magnetization with the functional parameters specified, check the **Mag Edge** box. To scale the exchange parameters with the functional parameters specified, check the **Exch Edge** box. Internal to LLG, the function that you specify is used to scale the existing magnetization and/or exchange parameter values.
3. Check the **Fix Torque** box if you want to keep the ratio of A/M constant.
4. Set the distance from the edge of the structure in the **Edge Distance** edit field.
5. Draw an edge in the graphic using the **Drawing Tool**. ***This feature cannot be used with an imported graphic***.
6. Right click the graphic and select **Specify Selection Region for Edge Property Effects** from the pop-up menu.
7. Use the **Picker Tool** (see page 71) to identify the change in properties along the edge.

Example:

1. Draw a square to define an edge.
2. On the **Main Page,** check **Set Params** and either **Internal** or **External Fill Region**, depending on whether you want to scale the edge internally or externally to the graphic.
3. On the **Edge Page**, check the **Mag Edge** box. Set A = 1, B = 0.4, C = 0 and D = 0. Click the **Plot** button.
4. Set the **Edge Distance** to 50nm.
5. Right click the window and select **Specify This Shape for Edge Property Effects**.
6. Right click the graphic and select **Fill Selected Region**.

Specifying Edge Roughness

To specify periodic **Edge Roughness**:

1. Specify which layers you want to mask on the **Mask Editor Main Page** and whether you want to turn on or turn off the region (internal or external).
2. Define a region with the Drawing Tool (see page 141).
3. Right click the graphic and select **Specify Selected Region for Edge Property Effects** from the pop-up menu.
4. Check the **Roughen Edge** box and specify the **Amplitude** and **Wavelength** of the roughness in the edit boxes.
5. Right click the graphic and select **Fill Selected Region** from the pop-up menu.

Specifying the Demagnetization Edge

When the square cells of your region are not aligned with the Cartesian axes, the edge of your structure will look like a staircase; in other words, the approximation to the edge is step-wise pulses. LLG can compute the demagnetization effects of edges that are not aligned with the grid. You can define a demag edge for three-dimensional problems only. Only one demag edge shape is allowed per problem. That shape can be a circle, an ellipse or an irregular polygon. The shape must lie in the x-y plane; it will be extruded so as to apply to all layers in z. The exchange interaction has been defined to be rigorous on 45 degree cuts. For all other cuts, the exchange is approximated using volume ratios of the cells. Therefore, a circular disk on a Cartesian grid problem will still have symmetry-breaking even when the edges are computed with this method. LLG will compute the eight in-plane nearest neighbors, the cell above, the cell below and the self-field using real-space sums. Each cell will be defined by a polygon, possibly irregular, of no more than six sides. The remaining terms are computed using Fourier transforms on the Cartesian grid. The additional expense to compute the demag edge is 11 x n, where n is the number of cells; in other words, the penalty is linear in the number of cells. To define the demag edge, you must first mask the cells that are external to the region. Once the cells are off, right click on the shape and select **Specify Selected Region for Demag Edge Calculation**. LLG will turn on any cells that are partially cut and the polygonal discretization of the boundary cells will shown.

IMPORTANT NOTE: With demag edge correction and Fourier transform methods for computing the demagnetization field, the first row of cells outside of the material will not have the correct demagnetization field values. To save time, the linear sums over the neighboring shaped edges for those cells in vacuum are omitted. Interior fields are correct. For energy methods of solving LLG, demagnetization fields are never computed in vacuum.

A Demagnetization Edge Problem

An example of the edge demagnetization problem is demonstrated below. The demagnetization field is computed along a row of cells adjacent to an edge of a 1-micron square by 20-nm thick Permalloy platelet. This computation was done for aligned grids using 5 and 10nm cell sizes and for 45 degree oriented platelets with and without the edge correction. In the figure, the 45 degree grid with the staircase edge shows marked errors in the computed demagnetization field, which are corrected using the edge algorithm implemented within LLG. The torque shown at the bottom graph are, again, more accurately represented in the edge correction scheme; although, the overall error is not so large as the effective field.

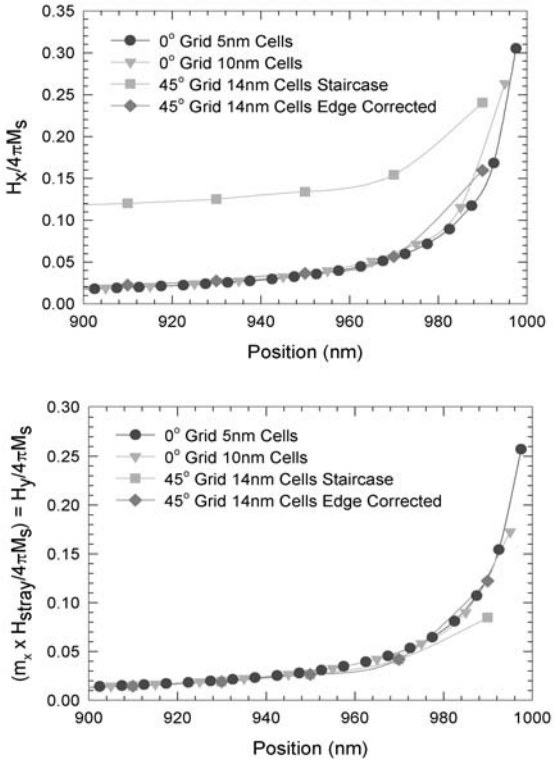


FIGURE 81. Edge Fields and Torques

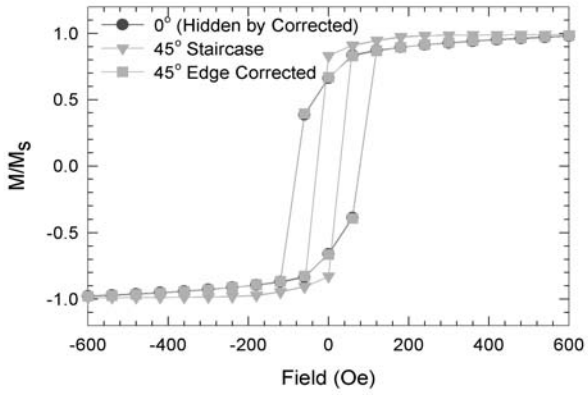


FIGURE 82. Computed Hysteresis Loops with and without Edge Correction

The staircase effect can lead to erroneous switching modes and switching fields. In the simple example shown above, the hysteresis loop is computed for a 100nm x 100nm x 10nm Permalloy platelet oriented along and at 45 degrees to the Cartesian axes. The edge-corrected loop falls on the oriented loop; in other words, they are the same. The staircase edge shows 100% error in the coercive field. The size and orientation of this example were selected to demonstrate the maximum effect due to the staircase approximation.

POSITION DEPENDENT PARAMETERS SHEET - BC PAGE

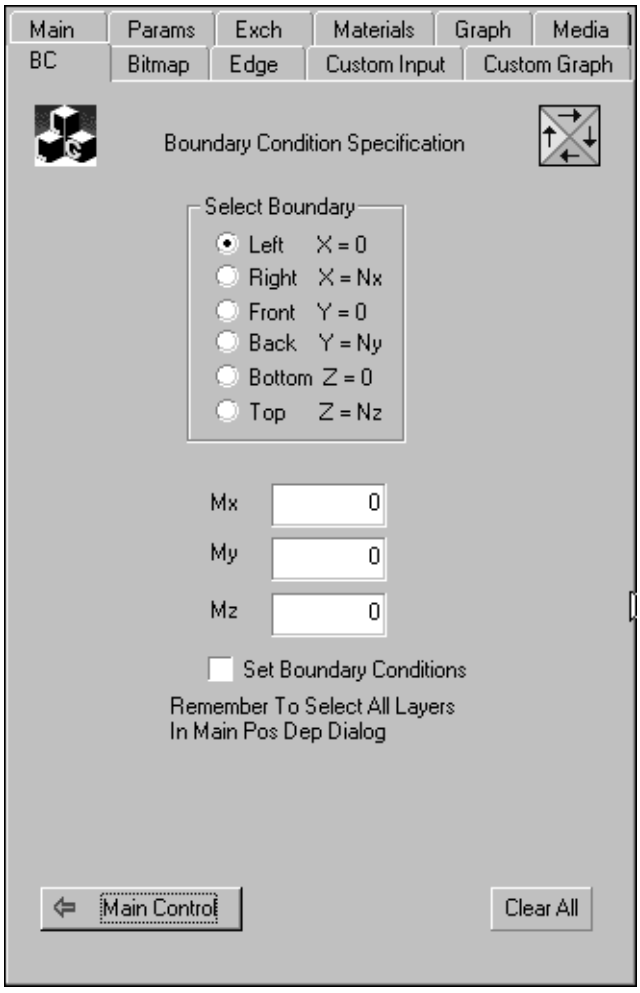


FIGURE 83. Position Dependent Parameters Sheet - Boundary Conditions Page

The **BC Page** is for setting the boundary conditions for position-dependent parameter problems.

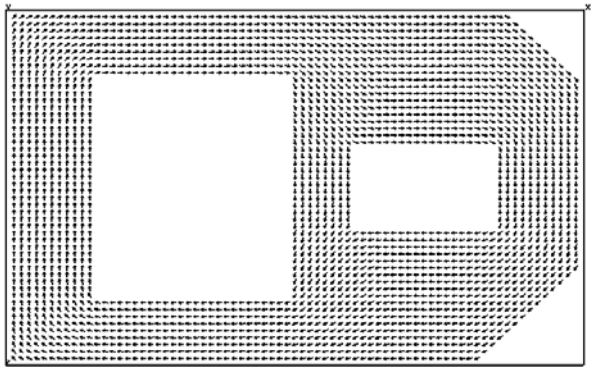
1. Select a region of interest using the drawing tool (see page 148).
2. Select the **Boundary Condition** that you want to change.
3. Set the boundary value in the **Mx, My** and **Mz** edit boxes.
4. Check the **Set Boundary Conditions** box to activate the boundary condition filler.
5. Right click the region of interest and select **Fill Region**.

Closing the Position Dependent Parameters Sheet

Once you have completed problem specification, it is strongly recommended that you save your parameters file using the **Save File** button. Then, you must click **Accept Changes** if you wish your changes to be recorded. Finally, you must click **Close PosDep Tool** to close the Position Dependent Parameters Sheet

CHAPTER 23

Simulation



The **Simulation Sheet** has six pages where you can fine tune your computation. Once you have specified your problem and started a computation, LLG computes the magnetostatic field coupling matrices and appropriate FFTs, if needed. The **Simulation Sheet-Simulation Page** is the master computation page. From the Simulation Page, you can toggle between running (**Start To Compute**) and pausing (**Pause**) your problem. You can visualize your problem as it evolves (**Turn Graphics On**) or just compute (**Turn Graphics Off**).

Remember, for faster computation speed, turn the graphics off!

PROGRESS STATUS INDICATORS

After every functional iteration, LLG updates the **Progress Status Indicators**. From one iteration to the next, the **Residual** is the largest change in any normalized magnetization vector. This is compared against the Convergence criteria. Each contribution to the total energy is displayed separately so that you can examine exactly how energies are traded as they are minimized. Remember that the ultimate integrity of an LLG solution is defined by its total energy; the best solutions have the lowest energies (for identical starting condition, etc.).

- The number of **Iterations**, **Simulation Time** and **CPU Time** are indicated after each computational cycle. The distinction between **Elapsed Time** and **CPU Time** is seen when the system has more than one processor. In such a situation, the CPU time will be greater than the elapsed time.
- When hysteresis loops are generated, the **Progress Hysteresis Indicators** chart progress. The number of field points completed, as well as the remanence at each cycle, is displayed to mark the calculation's progress.
- At lower left in the **Simulation Page** (shown on the following page), the status of the computation and the graphics are always indicated. The Red and Green lights on the buttons can be used to indicate the calculation's state.
- To evaluate the energy of a given configuration, click the **Update E** button. This computes the energy without taking a time step.

SIMULATION PAGE

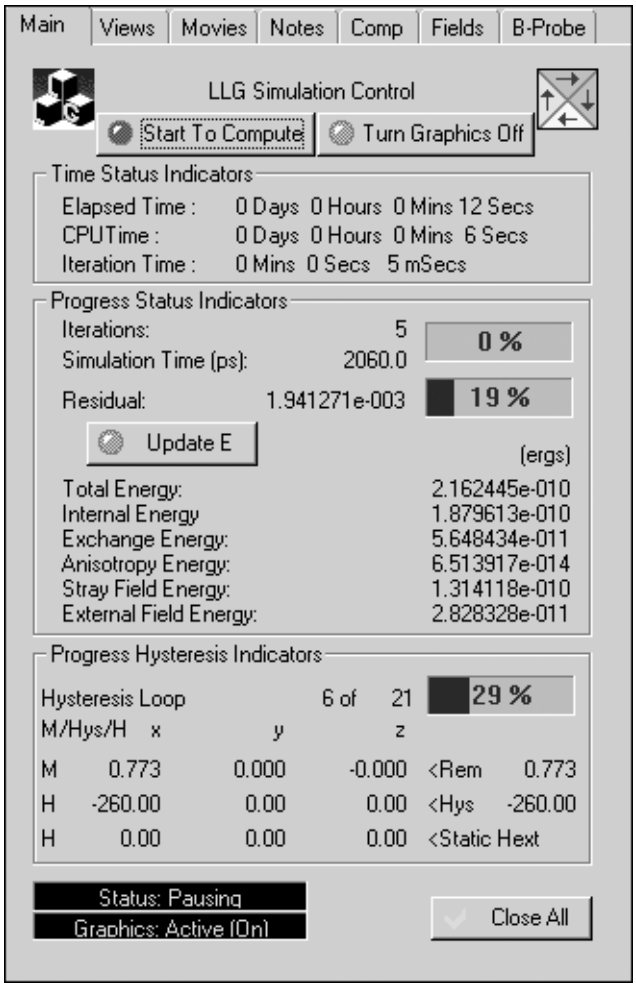


FIGURE 84. Simulation Sheet - Simulation Page

VIEWS PAGE

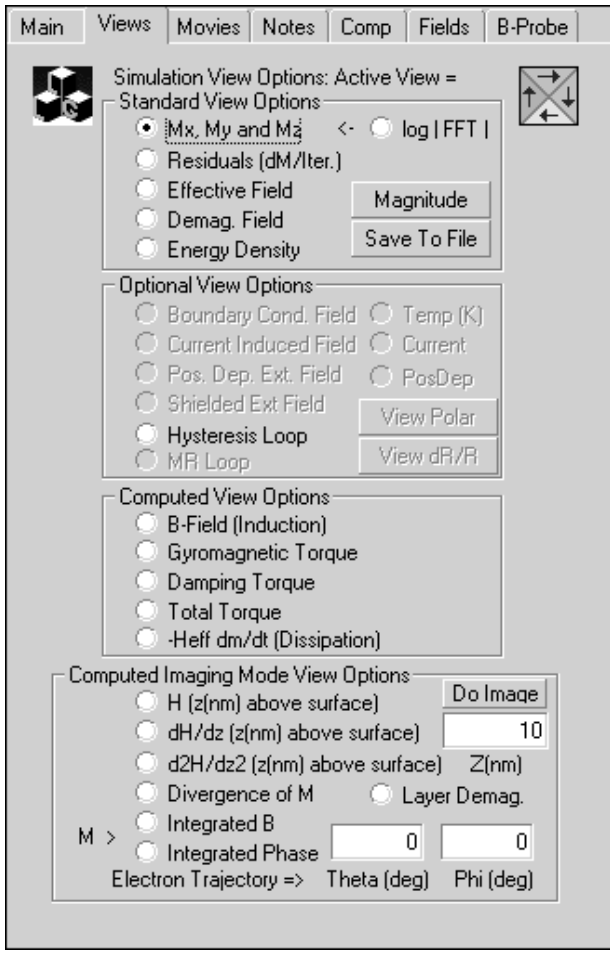


FIGURE 85. Simulation Sheet - Views Page

While LLG is running the computation, you can visualize different aspects of the problem. The View Options encapsulate typical micromagnetic parameters. You will probably be most interested in visualizing the direction cosines as they evolve during a simulation. However, there are instances when visualizing the effective, demagnetization or current-induced H-field can give you important insight into a problem. The OGL window can be recursively divided into sub-windows for viewing different aspects of the same problem. If you ***RIGHT CLICK*** on the main window, you have the options to split the window horizontally (resulting in two windows, one above the other), split the window vertically (resulting in two windows side by side) or delete the active window. You cannot delete the last window, as LLG requires that there be at least one active OGL window. You can continue to split the windows and make the nesting as deep as you choose.

VIEWING POSITION DEPENDENT PARAMETERS

Refer to page 150 for information on this feature.

You can put any view option into any view window. For demonstration, the **Magnetization Direction Cosines** Standard View Option is shown in several graphical representations. Other **View Options** are shown in one graphical representation. All **View Options** and graphics are drawn from the initial stage of the iteration process of the same sample problem; the parameters are: Simulation Volume: 500 nm for X(nm), 500 nm for Y (nm) and 30 nm for Z (nm); 50 sub-elements for N_x, 50 for N_y and 3 for N_z. Material Properties: Permalloy. Boundary Conditions: Left M_x = 1.0; Right M_x = 1.0 and X-directed current of 1000 μA. Computational Details: Relax All Points at Once - FFTs. Initialization: Vortex in Z.

Click the **Magnitude** button to plot the magnitude of any vector quantity. The data are stored in a temporary array and there is only one temporary array for each LLG object. This means that when you save data to a file from a **Computed View,** a **Computed Imaging Mode View** or a **Magnitude View** the data in the last LLG subwindow will be active. To ensure that you save the correct data to file, it is recommended that you use only one of these three views at a time.

STANDARD VIEW OPTIONS

MAGNETIZATION DIRECTION COSINES

With the **Magnetization Direction Cosines** Standard View Option, you can visualize the vector field whose projections are the normalized magnetization vectors along the three Cartesian axes.

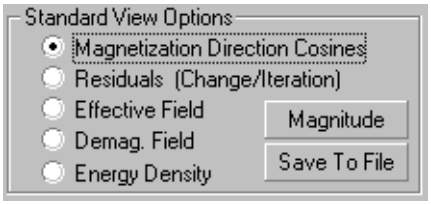


FIGURE 86. Standard View Options

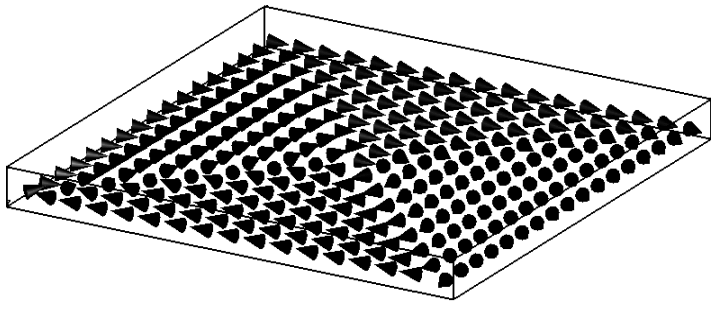


FIGURE 87. Magnetization Direction Cosine

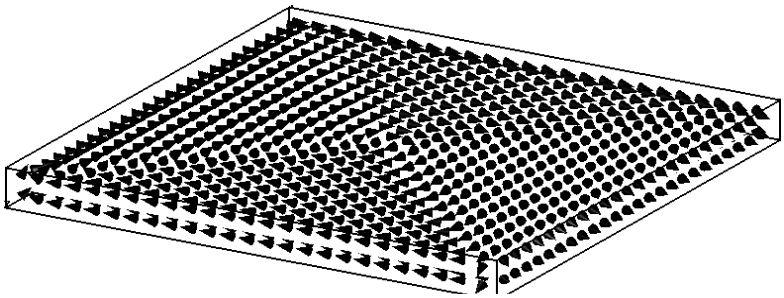


FIGURE 88. Magnetization Direction Cosine: 3D Cone

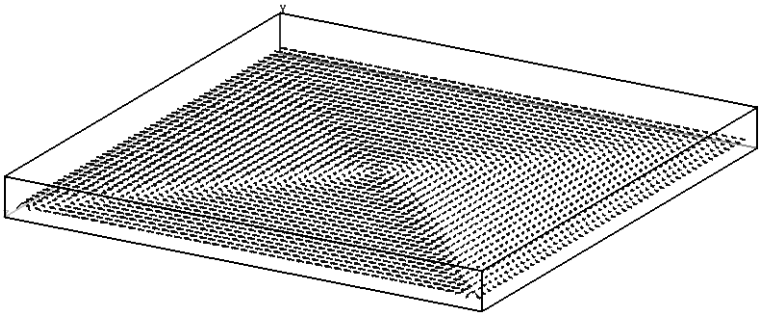


FIGURE 89. Magnetization Direction Cosine: Arrow Slice

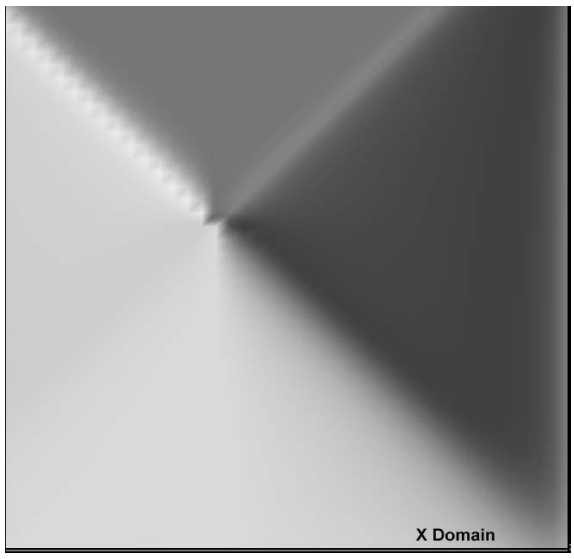


FIGURE 90. Magnetization Direction Cosine: Domain

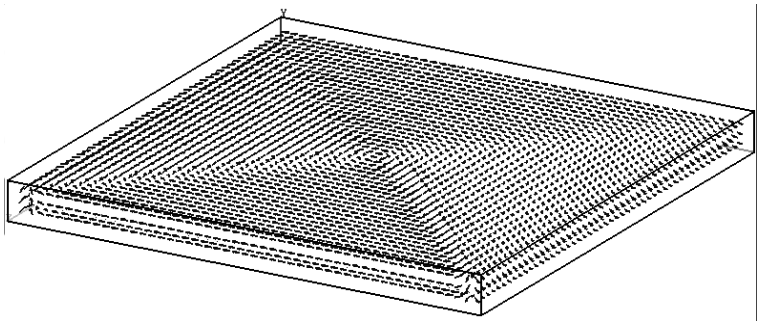


FIGURE 91. Magnetization Direction Cosine: 3D Arrows

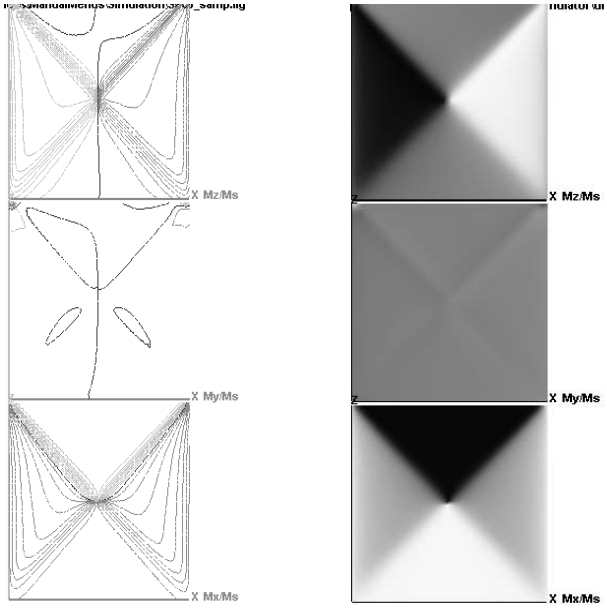


FIGURE 92. Magnetization Direction Cosine: Contour and Bitmap

You can superimpose 3D-cones with shading and texture on a bitmap. The procedure is as follows (Thanks Tony!)

a - select bitmap mode

b - check the 3d check box

c - change orientation to theta = 0.0 and phi = 270.0 (exactly)

d - check arrow overlay

e - check cones

f - turn on the OGL lights.

This procedure will make attractive 3D shaded cone overlays atop the bitmap images.

RESIDUALS (CHANGE ITERATION)

With the **Change/Iteration** option, you can visualize the vector field whose projections are the normalized residual vectors along the three Cartesian axes. The residuals are the result of the minimization or integration process and are defined within LLG as the vector difference between the current iteration's magnetization direction cosines and those of the previous iteration. The residuals decrease as the problem solution is approached.

Visualizing the residuals can be very helpful when an instability occurs, such as in the following cases:

- If the time step is too large, a common instability involving exchange causes adjacent cells to oscillate from iteration to iteration. When residuals are visualized in **Bitmap Graph Type**, adjacent rows of sub-elements oscillate between red and blue.
- You might be computing a large structure that is responding slowly during the iteration process. Or, there may be a domain wall across your structure that is moving rather slowly. You can use the view of the residuals to monitor the progress of this domain wall; if the wall is moving, the changes to the magnetization local to the wall are large and easily visualized.
- If your problem has loose spins that oscillate during a simulation as a result of a miscalculation of the appropriate mesh and set-up parameters, the view of the residuals allows you to identify which spin is loose.

EFFECTIVE FIELD

With the **Effective Field,** you can visualize the vector field whose projections are the normalized effective field vectors along the three Cartesian axes. The effective ‘magnetic’ field is the negative gradient of the energy density in a sub-element with respect to the magnetic moment in that sub-element. Therefore, the effective field includes external fields, exchange fields, anisotropy fields, demagnetization fields and any other fields resulting from terms that contribute to the free energy. The exchange field is defined as (on a Cartesian grid):

$$\vec{H}_{ex} = \frac{2A}{M_s \Delta^2} \sum_{nn} \hat{m}_i$$

DEMAGNETIZATION FIELD

You can visualize the vector field whose projections are the normalized demagnetization H-field vectors along the three Cartesian axes with the **Demagnetization Field** View Option. Use this to locate large demagnetization effects and to determine when they dominate nucleation and switching.

ENERGY DENSITY

You can visualize the scalar **Energy Density**. This is the only true scalar visualization mode. Since a scalar field cannot be visualized in a vector mode, with arrow fields for example, this option is synchronized with the **Bitmap Graph Type**.

OPTIONAL VIEW OPTIONS

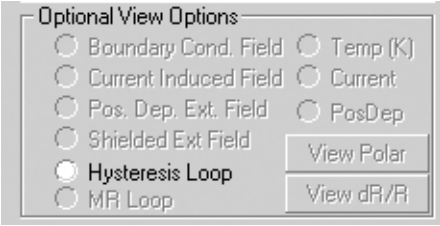


FIGURE 93. Optional View Options

BOUNDARY CONDITION FIELD

You can visualize the vector field whose projections are the normalized boundary condition H-field vectors along the three Cartesian axes. When your boundary conditions have components of the magnetization normal to the boundaries, there is a stray field within the sample volume due to the boundary conditions. LLG treats this field as an independent, externally applied, position-dependent field. In cases where such fields determine the nucleation and switching behavior of your system or of the magnetic microstructure within it, use the **Boundary Condition H-field** visualization tool to correlate the effect of the field with the resulting equilibrium magnetization.

CURRENT INDUCED FIELD

You can visualize the vector field whose projections are the normalized **Current Induced H-field** vectors along the three Cartesian axes. Use this View Option to visualize the field due to currents alone. Since currents are often used to bias the magnetization in MR heads, this allows you the flexibility of imaging that component of the magnetic field separately.

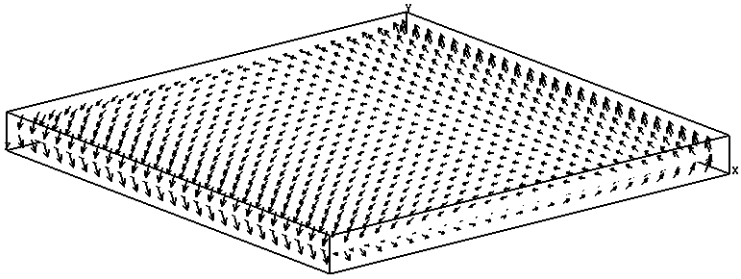


FIGURE 94. Current Induced Field: Arrows

POSITION DEPENDENT EXTERNAL FIELD

You can visualize the **Position Dependent External Field** when it is defined.

SHIELDED EXTERNAL FIELD

You can visualize the **Shielded External Field** when shields are specified and the loop is shielded.

HYSTERESIS LOOP AND MR LOOP

There are two additional **View Options** for visualizing MR and hysteresis loops. An **MR Loop** is displayed for LLG problems that have finite currents and non-zero AMR or GMR ratios. The **MR Loop** option allows you to toggle

between viewing the resistance R (the default) and the normalized differential resistance dR/R MR loop. The text on the button reflects the current state of the viewing tool.

A polar hysteresis loop is displayed for LLG problems with rotational hysteresis loops. The **View Polar** button lets you toggle between viewing the loop as a polar plot and as an angular plot. The text on the button reflects the current state of the viewing tool.

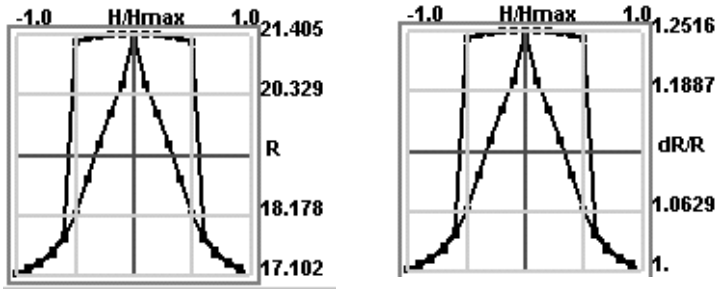


FIGURE 95. Polar Loops

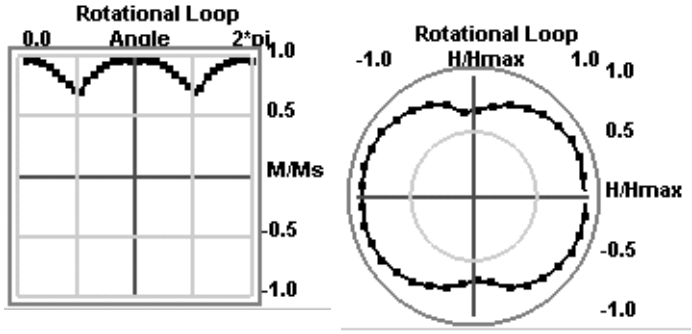


FIGURE 96. Polar Loops Represented in Polar and Angular Formats

COMPUTED VIEW OPTIONS

You can visualize several computed view options including **B-Field** (magnetic induction), **Gyromagnetic Torque**: (γ term in the LLG equation), **Damping Torque** (α term in the LLG equation), **Total Torque** and **-Heff dm/dt** (this is sort of a dissipation term, and is not completely rigorous due to the form of exchange field).

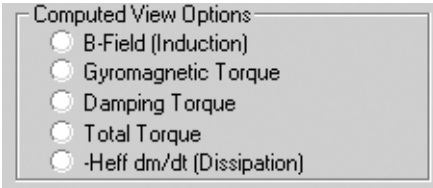


FIGURE 97. Computed View Options

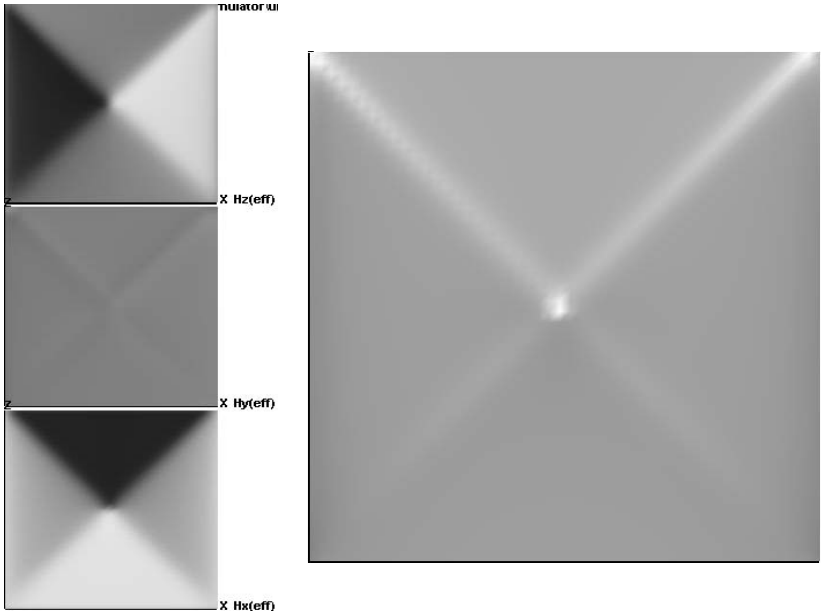


FIGURE 98. Energy Density and Effective Field Bitmaps

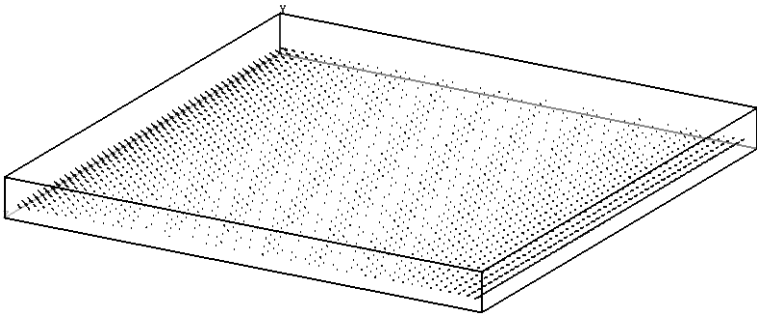


FIGURE 99. Boundary Conditions: Arrow Slice

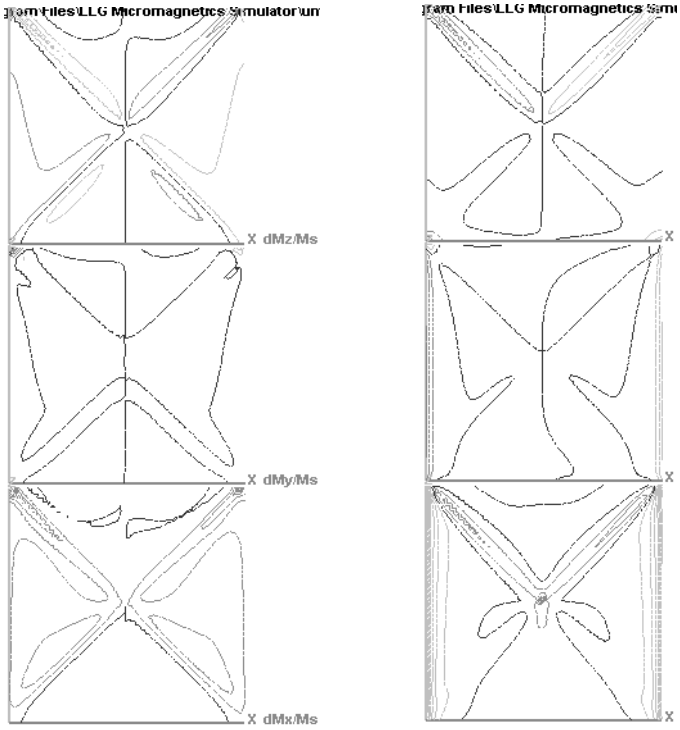


FIGURE 100. Change/Iteration and Demagnetization Field Contours

COMPUTED IMAGING MODE VIEW OPTIONS

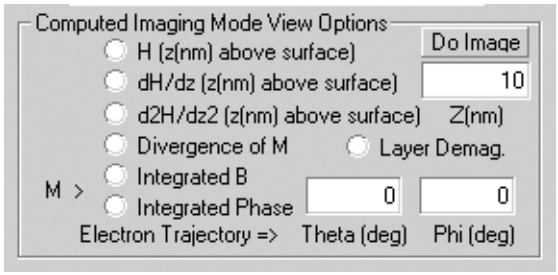


FIGURE 101. Computed Imaging Mode View Options

When you compute **H**, **dH/dz**, **d2H/dz2** or **Divergence M**, you must specify how far from the surface (actually how far from the center of the top layer of cells) to locate the scan. For example, 10nm converts to a scan height of 5nm above the surface, since the cells are each 10 thick. Once the image is computed, the results are put in the ***TOP*** layer of cells in Z. This means that, if you have a 10-layer system (in z), you must select the topmost layer (Nz=10) to see the view. This is to simulate that it is a surface view. To save the file, once it is viewed actively, click the **Save To File** button. The file will have the suffix llg_inputhfield. The data for that scan will be in the layer of cells that corresponds to the top layer of cells. In other words, if you have a 10-layer system and the top layer is z = 25.0 nm, that layer will contain the data. All other cells will have zero values

There are four MFM contrast modes for visualizing what your MFM would measure if it scanned above a given micromagnetic structure. LLG uses a rigid paradigm for rendering MFM images. LLG assumes that the surface of the structure of interest lies in the Z = constant X-Y plane. Enter the plane distance from the ***TOP*** of the structure in the edit box adjacent to the MFM mode selection, **H(z(nm) above surface)**, **dH/dz (z(nm) above surface)**, **d2H/dz2 (z(nm) above surface)** and **Divergence of M.** The MFM contrast for each mode will be computed for the plane of interest and displays. Electron microscopists might want to compute the **Integrated B-field** (TEM Lorentz) or **Integrated Phase** (DPC or electron holography). The angle of the incident beam must be specified in the **Theta (deg)** and **Phi (deg)** edit fields, where the angles are defined using the spherical coordinate convention defined in Chapter 5-LLG Environment.

You can also visualize demagnetization fields from independent layers. To do so, you must first create masks for the appropriate layers that you want to mask (or any portion thereof). Only the unmasked portion of the mask will be used in the demagnetization field computation. When you press **Do Image** LLG will prompt you for the input mask to read. LLG will then compute the demag field from only those cells that are unmasked. This will allow you to identify the position dependent dipolar coupling between layers for MRAM and similar applications.

IMPORTANT NOTE:

H(z), dH(z)/dz and $d^2H(z)/dz^2$, Integrated B and Integrated Phase images take time to compute. The **Do Image** button has been strategically placed for you to indicate to LLG that you want an image to be computed. The computed images store data in a common temporary array. You can view only one computed image at a time because the data are stored in a common area.

.

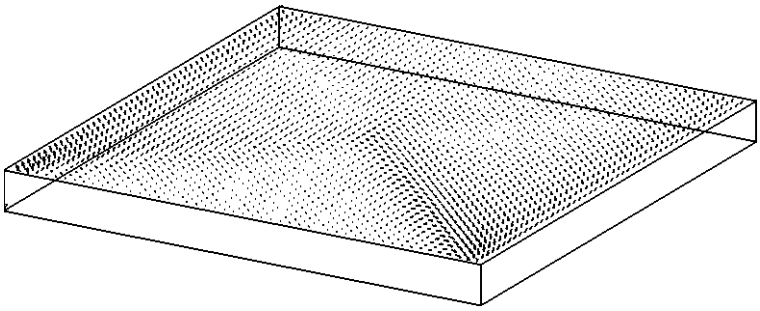


FIGURE 102. Computed Imaging Mode: Fields/Arrow Slice

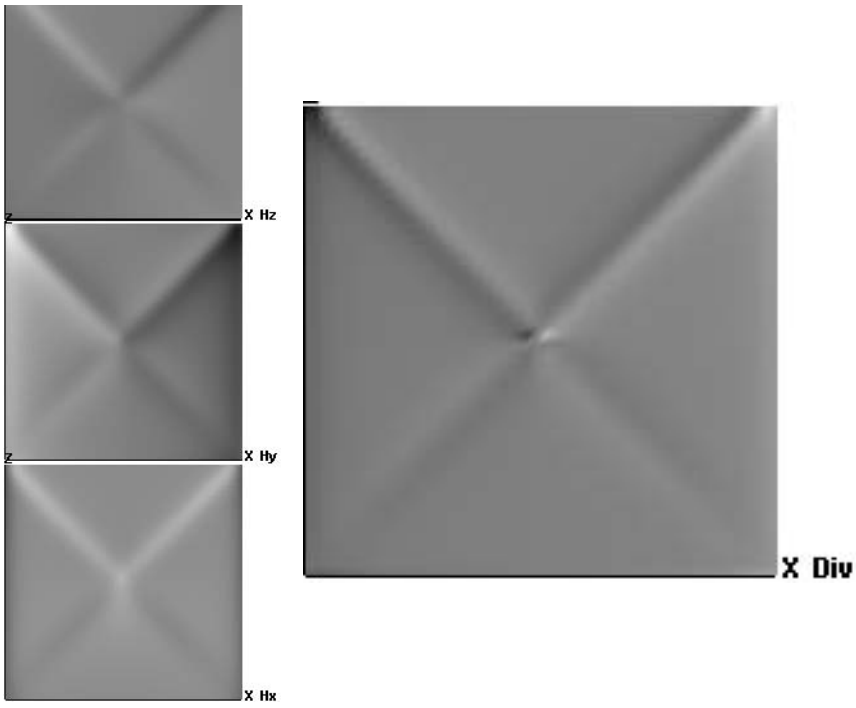


FIGURE 103. Computed Imaging Mode: Fields and Divergence of M Bitmaps

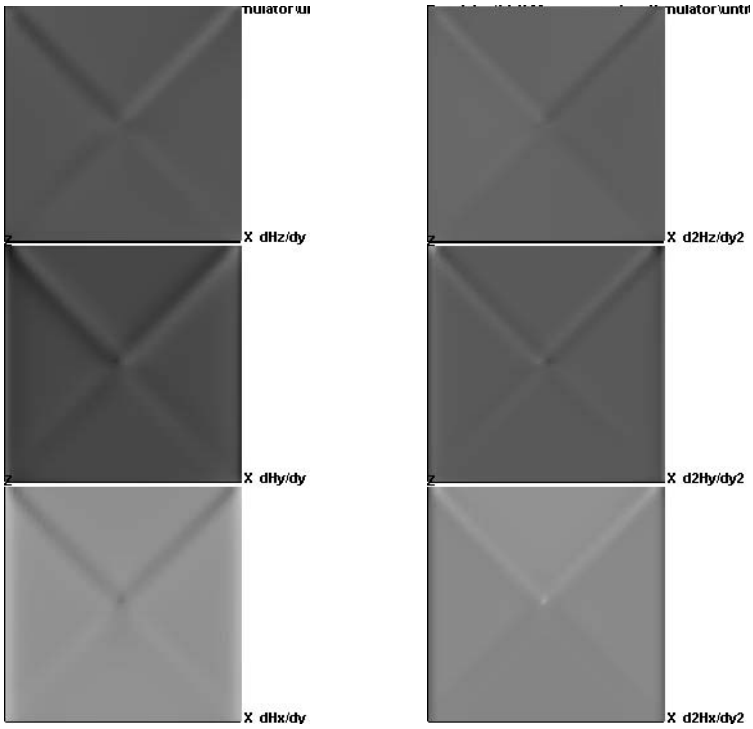


FIGURE 104. Computed Imaging Mode: dH/dz and d^2H/dz^2 Bitmaps

SAVING TO FILE

To save any active view data to a file, left click on the view, then click the **Save to File** button to assign a file name. H(z), dH(z)/dz and $d^2H(z)/dZ^2$ are surface properties and data are stored as the top-most slice in Z in the file; the rest of the cell data are set to 0.0.

IMPORTANT NOTE: Current Field Files are saved with the current scaled to 1 microamp. As LLG internally varies current with time, all spatially dependent currents are derived from test currents of 1 microamp. To recover true field values from the saved files, multiply the saved field values by the real current in microamps.

TIME DEPENDENT FIELD H(T), CURRENT I(T) AND FMR VISUALIZATION

When time dependent fields, currents or FMR fields are used, the simulation view page will change to reflect the simulation mode.

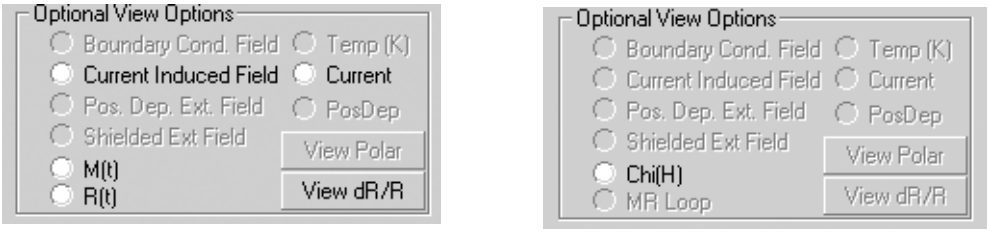


FIGURE 105. Simulation view for H(t) and I(t) (left) and FMR (right).

Below, examples of the time dependent magnetization, magnetoresistance and suseptibility are illustrated for the cases defined above. The magnetizations in color have r-g-b connected to x-y-z components of M.

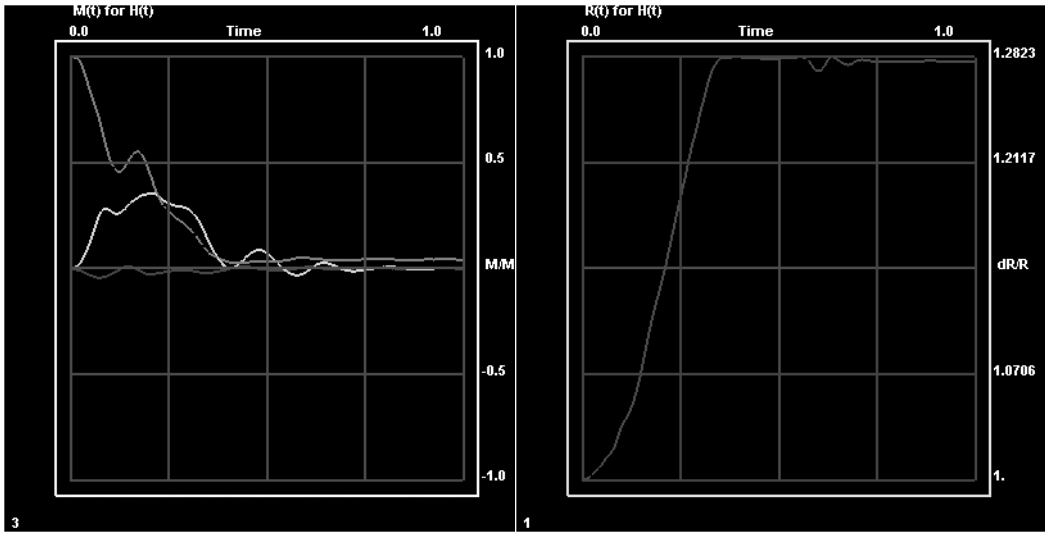


FIGURE 106. M(t) and R(t).

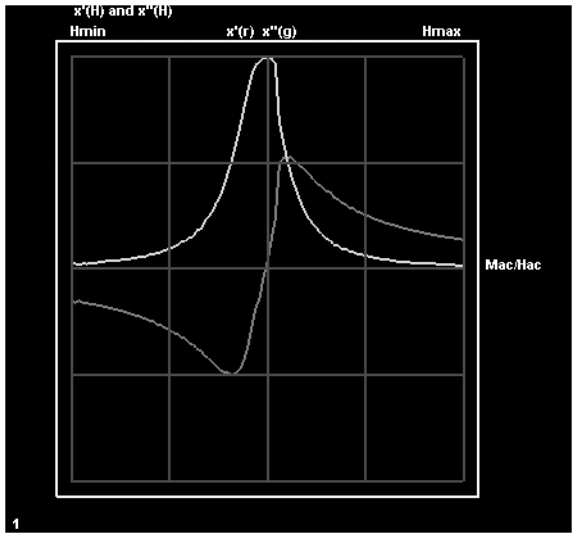


FIGURE 107. x'(H) and x"(H)

MOVIES PAGE

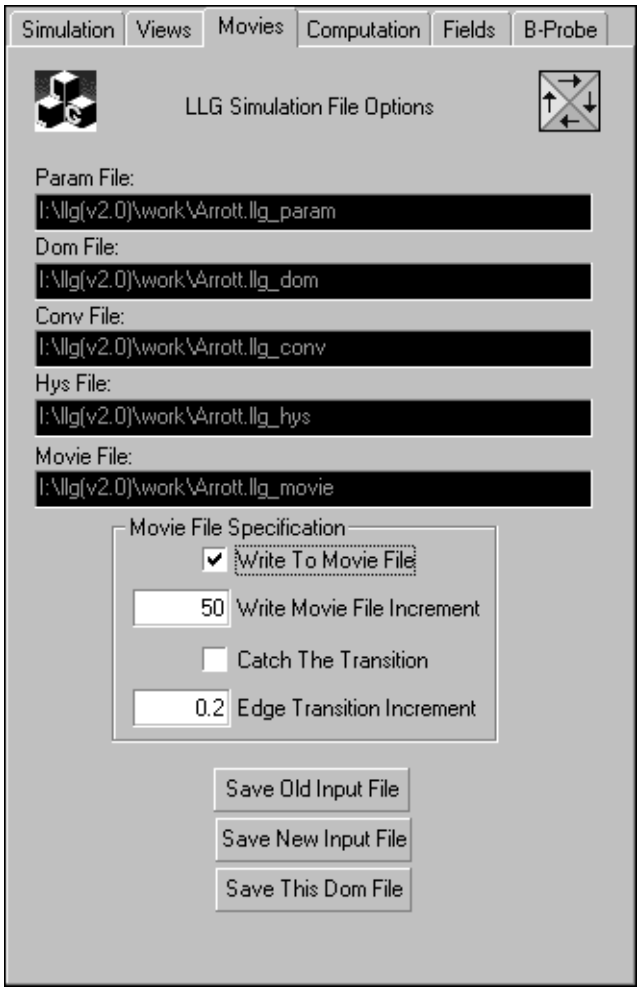


FIGURE 108. Simulation Sheet - Movies Page

The **Simulation Sheet-Movies Page** is where you specify movie options prior to starting to simulate (integrate) for the first time. You must define movie options before you start a computation, since you will not have another chance to change or update them once a simulation is initiated. The file names for standard LLG output files are summarized for your convenience. Additionally, while the calculation is paused, you can **Save This Dom File** at any time during a calculation. As you can modify the computational parameters after a calculation has started, there is an extra option to save a v1 (**Save Old Input File**) or a v2 (**Save New Input File**) to disk for later use.

SAVING A MOVIE TO DISK

To save a movie to disk, you must check the **Write To Movie File** box. The **Write Movie File Increment** option is for saving time slices during a time-dependent calculation to a file. Long calculations produce even longer movies, so choose the **Write Movie Time Increment** carefully.

SAVING DOMAIN STATES DURING A HYSTERESIS LOOP

Sometimes you might want to save the domain states during a hysteresis loop, even though you are not at the equilibrium state for that field. LLG terms this “catching the transition.” Check the **Catch The Transition** box if you want to do this. Set the **Edge Transition Increment** to a value between 0 and 1. If you set the value at 0.2, then when each value

that is passed for remanence, 1.0, 0.8, 0.6 and so on, a movie sheet will be written to the file. In this way, you can capture transition states if your baseline field points are too coarsely separated.

COMPUTATION PAGE

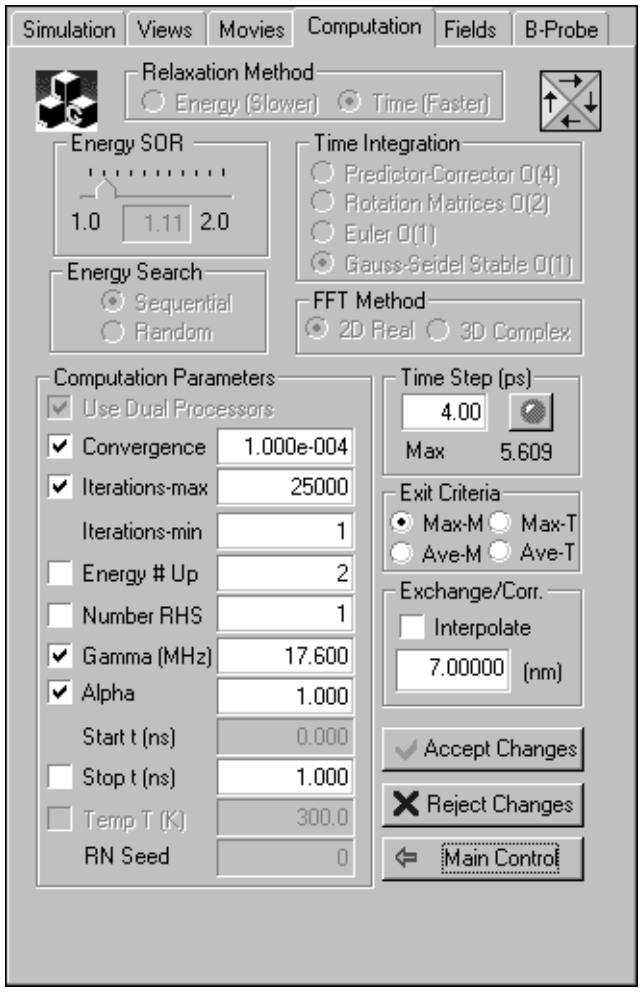


FIGURE 109. Simulation Sheet - Computation Page

You can update computational parameters, such as the **Time Step** and the **Convergence** criteria, during a calculation. As in v1, you cannot change a major computation mode, such as going from an energy method to an FFT method. Please see Chapter 10-Input Sheet-Computation for a complete discussion of the parameters on this page.

FIELDS PAGE

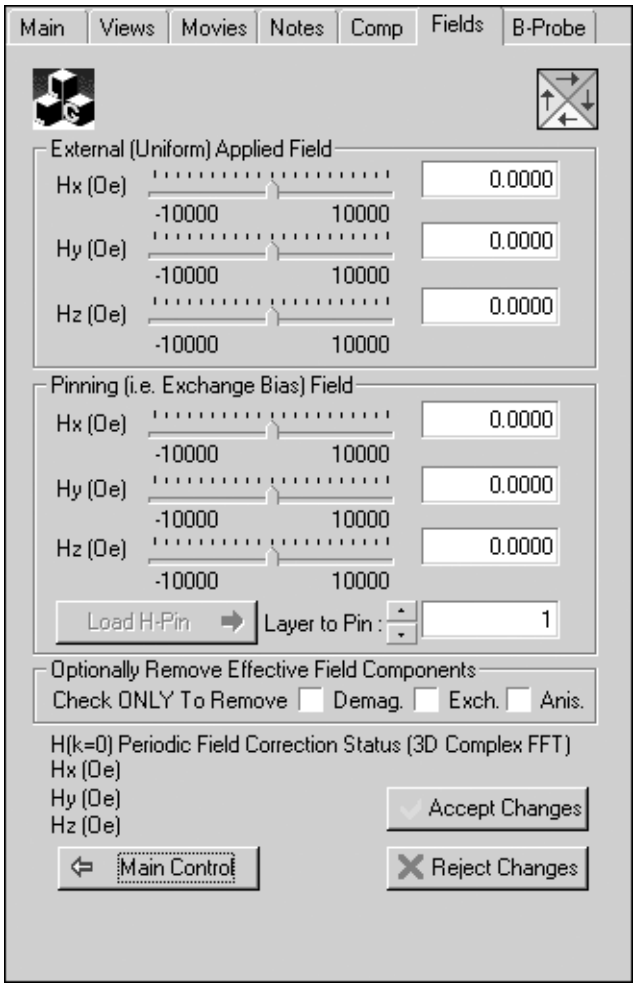


FIGURE 110. Simulation Sheet - Fields Page

You can update field parameters during a calculation. Refer to Chapter 12-Fields (page 75) for a complete discussion of the parameters on this page.

B-PROBE PAGE

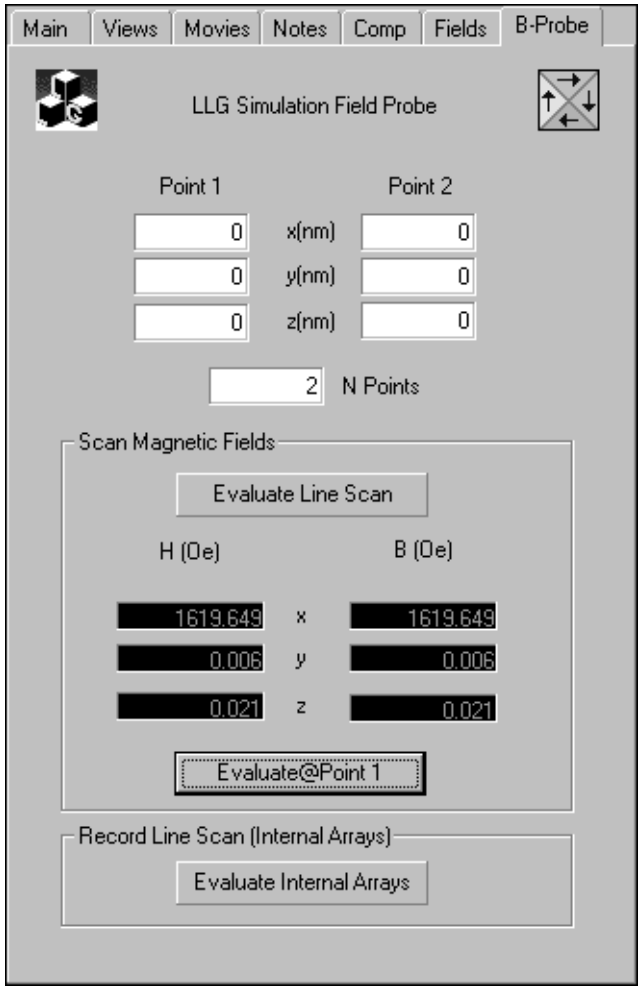


FIGURE 111. Simulation Sheet - B-Probe Page

You can use the **B-Probe Page** to calculate the B- and H-fields anywhere inside or outside of the Simulation Volume. To sample the field at one point, enter the coordinates in nanometers into the **Point 1** edit boxes and click the **Evaluate @Point 1** button. The B- and H-field components will appear beneath **H (Oe)** and **B (Oe)**.

To store a line scan, enter the starting and ending point coordinates in the **N Points** edit box. Click the **Evaluate Line Scan** button and you will be prompted for a file name in which to store the line scan data. When computing fields interior to the Simulation Volume, you ***MUST*** be sure that the sampling point coordinates are coincident with the locations of the magnetization moments in the grid. Since this calculation mode uses the fields from point dipoles, the field value will begin to diverge if you are arbitrarily close to a dipole.

CLOSING DOWN A CALCULATION

To end a calculation, pause the calculation and then shut down LLG by clicking the **Close All** button on the **Simulation Page**.

GUIDELINES FOR RUNNING LLG SIMULATIONS

Modeling problems with LLG involves some subjective (interpretive) judgement on your part. The Input Phase demands precision in data entry. However, the data used to specify a problem in LLG is only a MODEL. How well this model replicates a physical system depends upon many features including whether you have:

- Matched the size and shape of the structure.
- Included observable physical imperfections, such as vacancies or roughness.
- Assigned the correct macroscopic magnetic parameters to the regions of interest.
- Specified field values for the hysteresis loops that saturate the system.
- Assigned the mesh density appropriately.
- Set the convergence and exit criteria appropriately.

Oversights in the Input Phase manifest themselves during the Simulation Phase in two typical ways: solutions oscillate and fail to converge, and the iteration process terminates prematurely.

Your Problem Fails to Converge

LLG may not produce meaningful solutions when the mesh density is too coarse or when the quasi-time step has been set too large. Examine the iteration history when running a problem that you suspect (or it may be extremely obvious!) may be unstable. Pause the simulation and visualize the Change/Iteration in the Bitmap Graphics Type.

Time Step Too Large

Subtle, and sometimes not so subtle, instabilities caused by exchange appear when neighboring moments oscillate. In the Change/Iteration - Bitmap Graphics Type, you will see oscillating parallel lines of red and blue. This happens in any of the parallel (FFT or time integration) computing modes when the time step is too large. Pause the simulation and decrease the time step.

Grid Too Coarse

If the grid is too coarse, your problem may never converge! In both the 1-pt and FFT-based methods, problems defined on course grids oscillate wildly. Since the grid stability is related to the specified parameters, a general rigid rule can not be given for all situations. However, as a rule of thumb, Permalloy sub-element sizes should be no larger than about 10 nm and Fe sub-element sizes should be no larger than about 7 nm. If your problem becomes unstable and resetting the time step or accelerator does not remedy the instability, Pause then terminate the simulation! Restart the problem and increase the grid density! The goal is to define as coarse a grid as possible while maintaining stability, as this saves CPU time.

Exiting the Iteration Process Prematurely

The validity of the solution depends upon whether the local energy minimum has actually been reached. This criterion is difficult to specify analytically, since LLG solves non-linear integro-differential equations. LLG provides several control parameters to help you specify how accurate a solution your problem requires. The outcome from setting the convergence criteria too coarsely can be severe, that is, you might get the wrong coercive field or even the wrong final magnetization state. When you are performing an important problem, bracket the solution by repeating the calculation with a range of exit criteria to test the robustness of your solution.

GUIDELINES FOR SETTING UP PROBLEMS AND DECREASING COMPUTATION TIME

The following are essential features for solving a real micromagnetics simulation problem.

- Know your problem. Simulate only the part of your system that is relevant. You need not simulate each and every part at once.
- Start small. Model a subset of your problem. If you have a large problem, establish the key features by constructing a miniature version of your problem. Small problems run quickly and can be visualized and tested interactively.
- Find the appropriate settings (convergence, time step and mesh density) for your miniature model problem.
- Do not simulate a hysteresis loop. Run the zero-field problem first.
- Find the coercive field manually; increase the statically applied external magnetic field. Knowledge of the coercive field allows you to optimize the hysteresis loop sampling later.
- Watch the problem evolve; interact with it and experiment with modifying the parameters to identify those that must be specified accurately.

MOVIE PAGE (SIMULATE A MOVIE OPTION)

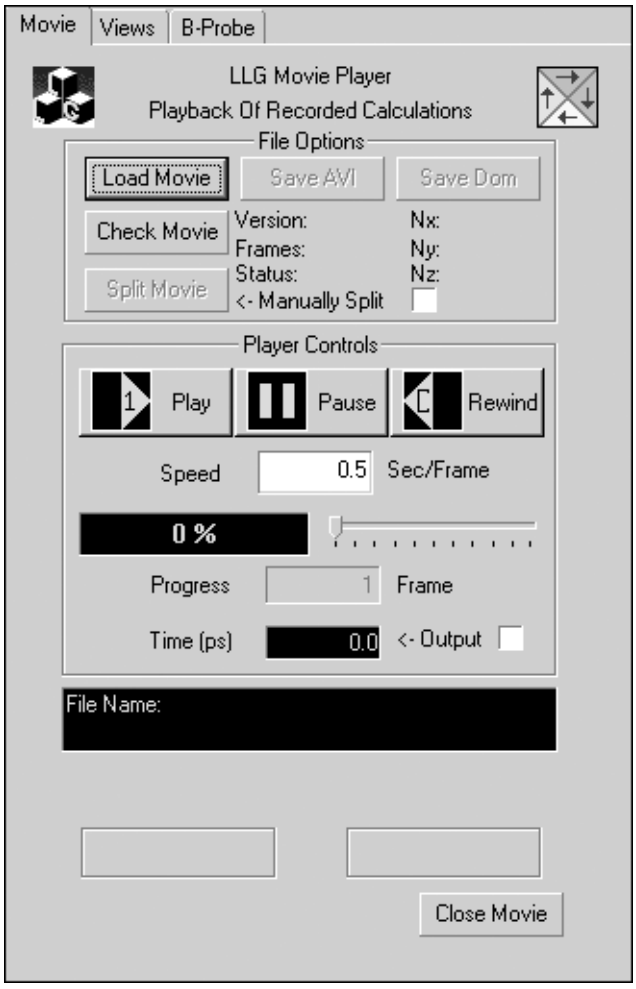


FIGURE 112. Simulation Sheet - Movie Page (Simulate a Movie Option)

You can load and play a movie through your simulation. For explicit instructions on loading and playing movies, refer to Chapter 25 - Movie Viewer. The movie that you load through this page with the **Simulate a Movie** option ***MUST*** have the same number of pixels in each dimension in the Simulation Volume as those specified in the Main Page. This option allows you to play the movie, visualize the magnetization, effective fields, energy densities and residuals simultaneously. You can restore all essential simulation details in the short time it takes to play the movie.

BATCH MODE PROCESSING

LLG features ***batch mode*** processing. In batch mode, there is no graphical data representation. A very simple user interface allows you to keep track of LLG's activities and progress. The batch mode processor is based upon a list file. This list file is a compilation of LLG parameter files, each with an embedded list of auxiliary input files (masks, posdep files, and initialization files etc.). The batch mode file can be loaded as a list of individual parameter files or generated automatically by the **batch mode scripting** engine. This allows you to instruct LLG to run sequential problems, perhaps varying parameters or initial conditions between sequential runs.

SETTING UP THE BATCH MODE EXECUTABLE

LLG's batch mode processor is embedded in the LLG executable kernel. It uses the same engine as the GUI enabled LLG (i.e., the same classes and files, etc.). To set up LLG to run in batch mode:

- Create a new link to llg_v2.exe using the task bar.
- When you are prompted for the command line, add ***/b*** to the end. On a typical system, the command line looks like ***D:\llg(v2.0)\llg_v2.exe /b***.
- When prompted to name the link, choose something like ***llg_v2_batch***. (Note: For DOS friendly users, you can open a DOS window, change directories to the LLG executable directory, and type the command ***llg_v2.exe /b*** to obtain the same results.) The batch mode interface, shown below, appears (with a bath file already loaded).

.

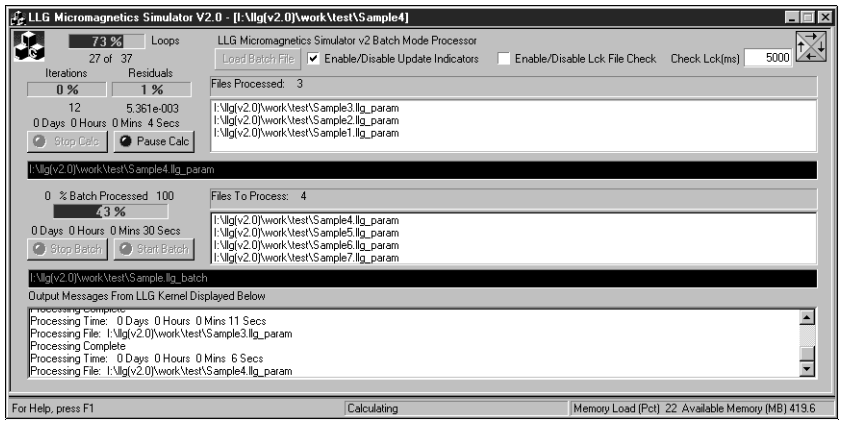


FIGURE 113. Batch Mode Interface

LOADING A BATCH FILE

To load a batch file, click the **Load Batch File** button. The suffix for batch mode files is *.llg_batch. You will see a list of files loaded into the **Files to Process** list control.

CLEARING A BATCH MODE FILE STREAM

To stop or clear a batch mode processing completely, click the **Stop Batch** button. The files that remain to be processed and those that have been processed will be cleared.

STARTING A BATCH PROCESS

To start a batch process, click the **Start Batch** button. This activates the process and enables the **Pause Calc** button. As the files are processed, the **Iterations** progress bar and **Residuals** progress bar track the calculation's progress. You can disable these monitors by checking the **Enable/Disable Update Indicators** box. While this control is checked, the interface is updated. As the process runs, LLG will also report on elapsed times for the problem and the batch. As each problem is run, the problem name appears in the topmost (black and green) file banner. Once the computation is

complete, the name of the file moves to the **Files Processed** list control. LLG reports batch mode status to the output window at the bottom of the dialog box, and concurrently writes this data to a log file (*.llg_batch_log).

Pausing a Batch Mode Calculation

To pause a batch mode calculation, click the **Pause Calc** button. To resume a paused calculation, click the **Start Batch** button. To terminate a problem, click the **Stop Calc** button. If there are other files to process in the list, the batch mode will begin processing the next problem.

Monitoring a Batch Mode Calculation

While running computations, LLG continues to write standard output files. If you opted to store a movie, or write to a convergence file at a defined number of iteration steps, you can examine these files during the batch mode computation to see the progress of your problem. You can use the GUI-enabled LLG to look at your partially written movies or to load the convergence file into the **2D Graphics** environment (page 55). You can keep track of the details of your calculation by using these existing LLG tools.

Setting Up a Batch Mode Process

An LLG batch file is simply a list of *.llg_param files. You can use a standard editor to create this list (you must use the full path name including the disk, as D:\MyDirectory\MySubDirectory\MyFile.llg_param) or use LLG to create the batch mode file for you. The fundamental difference between batch mode processes and interactive processes is that, in batch mode processes, you must define the input variables prior to loading the parameter file into the LLG execution kernel.

Editing Batch Files

At any time while LLG is running in batch mode, you can edit the contents of any parameter file set to run in the batch, even if the file is already in the **Files To Process** list. In this way, LLG remains fully compliant to interactive changes up to the moment that the parameter file is loaded to run.

LLG has the capability of loading the following files at run time:

- *.llg_mask (mask file)
- *.llg_posdep (position dependent parameter files)
- *.llg_dom (initial angle files)
- *.llg_inputhfield (boundary condition field)
- *.llg_inputhfield (current field)

Batch mode processor allows the names of these files to be added to the end of the parameter file, with a flag indicating whether or not a particular process is to be activated. In this way, LLG can run any type of simulation, as long as the appropriate files are available at run time. As of this release, all llg_param files contain the necessary file elements added to the parameter output file for batch mode processing.

The file names can be specified on the **Input Sheet-Batch Page** (click the Batch tab). There are six check boxes. You must check the box to signal LLG (batch mode only) to use the attached file for processing. You can enter the names of the files in the edit boxes or search for them by clicking the buttons to the right of the edit fields. This provides you with the option of loading an existing file (named) or specifying a file yet to be created by a future LLG batch run. However, note that the specified file must have been written by the time the problem being specified is to be run.

Note: LLG writes comments on batch problem variations to the **Input Sheet- Notes Page** (page 121).

EXTERNALLY CONTROLLING BATCH MODE PROCESSING

When you check the **Enable/Disable Lck File Check** box at the top of the **Batch Mode Interface**, LLG searches for a file with the _lck extension (that is, your batch file is C:\MyLLG\SampleBatch.llg_batch and the lck file must have the name C:\MyLLG\SampleBatch.llg_Batch_lck). When LLG finds a lock file, it pauses the calculations. LLG checks that this file exists every **Check Lck(ms)**, as entered in the edit box at the top right of the **Batch Mode Interface**. You can modify any file still in the queue that has not been processed, or you can add or delete any param file from the **Files To Process** list box. This gives you the flexibility of modifying the batch file's actions as the file progresses. The file-based lck mechanism allows you to make changes over a network or remotely. Once the lck file is gone, LLG begins processing the next file in the queue. Please note that the lck file interrupt occurs only between the calculations of individual param files; no checking occurs during the calculation itself.

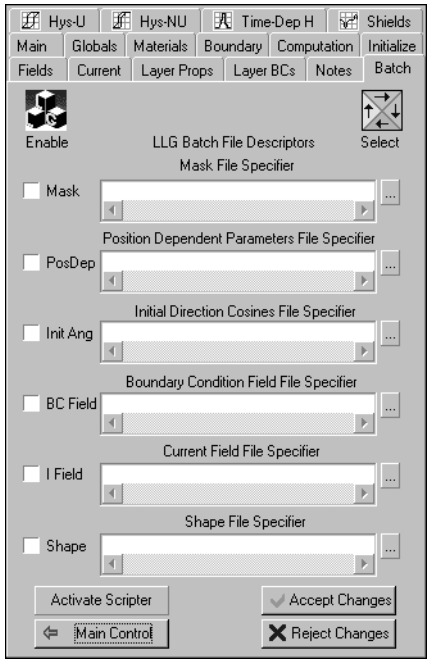


FIGURE 114. Batch Page of Input Sheet for File Name Specification

Using the Scripting Interface

You can use the batch mode scripting interface to write batch files directly using a search, or you can make variations on an existing problem by loading an existing *.llg_param file and looping through the parameters. You activate the scripting engine by clicking the **Activate Scripter** button in the **Batch Page** or by clicking the script **SCR** icon in the Tool Bar.

GENERATING A BATCH FILE USING A LIST OF EXISTING FILES

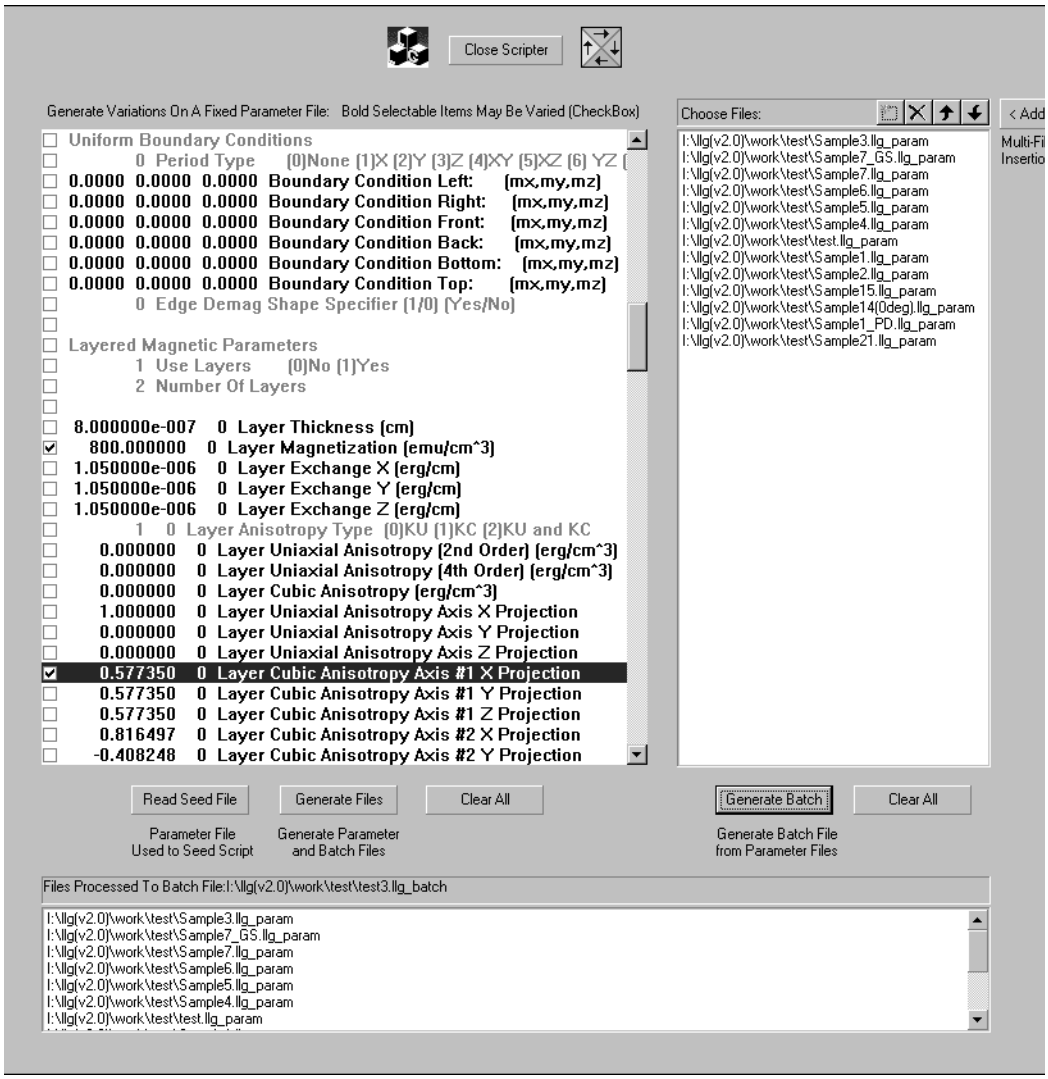

Close Scripter
Generate Variations On A Fixed Parameter File: Bold Selectable Items May Be Varied (CheckBox)
Uniform Boundary Conditions
0 Period Type (0)None (1)X (2)Y (3)Z (4)XY (5)XZ (6) YZ
0.0000 0.0000 0.0000 Boundary Condition Left: (mx,my,mz)
0.0000 0.0000 0.0000 Boundary Condition Right: (mx,my,mz)
0.0000 0.0000 0.0000 Boundary Condition Front: (mx,my,mz)
0.0000 0.0000 0.0000 Boundary Condition Back: (mx,my,mz)
0.0000 0.0000 0.0000 Boundary Condition Bottom: (mx,my,mz)
0.0000 0.0000 0.0000 Boundary Condition Top: (mx,my,mz)
0 Edge Demag Shape Specifier (1/0) (Yes/No)
Layered Magnetic Parameters
1 Use Layers (0)No (1)Yes
2 Number Of Layers
8.000000e-007 0 Layer Thickness (cm)
800.000000 0 Layer Magnetization (emu/cm^3)
1.050000e-006 0 Layer Exchange X (erg/cm)
1.050000e-006 0 Layer Exchange Y (erg/cm)
1.050000e-006 0 Layer Exchange Z (erg/cm)
1 0 Layer Anisotropy Type (0)KU (1)KC (2)KU and KC
0.000000 0 Layer Uniaxial Anisotropy (2nd Order) (erg/cm^3)
0.000000 0 Layer Uniaxial Anisotropy (4th Order) (erg/cm^3)
0.000000 0 Layer Cubic Anisotropy (erg/cm^3)
1.000000 0 Layer Uniaxial Anisotropy Axis X Projection
0.000000 0 Layer Uniaxial Anisotropy Axis Y Projection
0.000000 0 Layer Uniaxial Anisotropy Axis Z Projection
0.577350 0 Layer Cubic Anisotropy Axis #1 X Projection
0.577350 0 Layer Cubic Anisotropy Axis #1 Y Projection
0.577350 0 Layer Cubic Anisotropy Axis #1 Z Projection
0.816497 0 Layer Cubic Anisotropy Axis #2 X Projection
-0.408248 0 Layer Cubic Anisotropy Axis #2 Y Projection
Choose Files:
I:\llg(v2.0)\work\test\Sample3.llg_param
I:\llg(v2.0)\work\test\Sample7_GS.llg_param
I:\llg(v2.0)\work\test\Sample7.llg_param
I:\llg(v2.0)\work\test\Sample6.llg_param
I:\llg(v2.0)\work\test\Sample5.llg_param
I:\llg(v2.0)\work\test\Sample4.llg_param
I:\llg(v2.0)\work\test\test.llg_param
I:\llg(v2.0)\work\test\Sample1.llg_param
I:\llg(v2.0)\work\test\Sample2.llg_param
I:\llg(v2.0)\work\test\Sample15.llg_param
I:\llg(v2.0)\work\test\Sample14(0deg).llg_param
I:\llg(v2.0)\work\test\Sample1_PD.llg_param
I:\llg(v2.0)\work\test\Sample21.llg_param
Read Seed File
Generate Files
Clear All
Generate Batch
Clear All
Parameter File Used to Seed Script
Generate Parameter and Batch Files
Generate Batch File from Parameter Files
Files Processed To Batch File:I:\llg(v2.0)\work\test\test3.llg_batch
I:\llg(v2.0)\work\test\Sample3.llg_param
I:\llg(v2.0)\work\test\Sample7_GS.llg_param
I:\llg(v2.0)\work\test\Sample7.llg_param
I:\llg(v2.0)\work\test\Sample6.llg_param
I:\llg(v2.0)\work\test\Sample5.llg_param
I:\llg(v2.0)\work\test\Sample4.llg_param
I:\llg(v2.0)\work\test\test.llg_param

FIGURE 115. Batch Mode Scripting Interface

To generate an LLG batch file from existing *.llg_param files, use the list control at right to load named files into the list. Once the list is complete, click the **Generate Batch** button; you will be prompted for a batch file name and location. Files may be deleted, reordered and cleared from the list. The **Clear All** button clears the entire list.

VARYING BATCH PROBLEMS AND SCRIPTING

You can load a single problem and examine its contents for varying selected parameters. Click the **Read Seed File** button in the **Scripting Interface** to load a selected parameter file. The controls (not shown above) at left allow you to examine the contents of this file using the standard LLG input tools. When you load a file, the input controls are updated with the required parameters. You can vary up to five parameters at a time using the scripting engine (a nested loop five deep). The parameters that can be modified are in black (as opposed to dark grey); check each one that you want to change. In the **Scripting Interface** shown, the magnetization and uniaxial anisotropy parameters have been selected for variation. You can select at most five parameters to vary. Once you have selected the parameters, click the **Generate Files** button. For each parameter that you select, you will be prompted by LLG to enter parameters, as shown below.

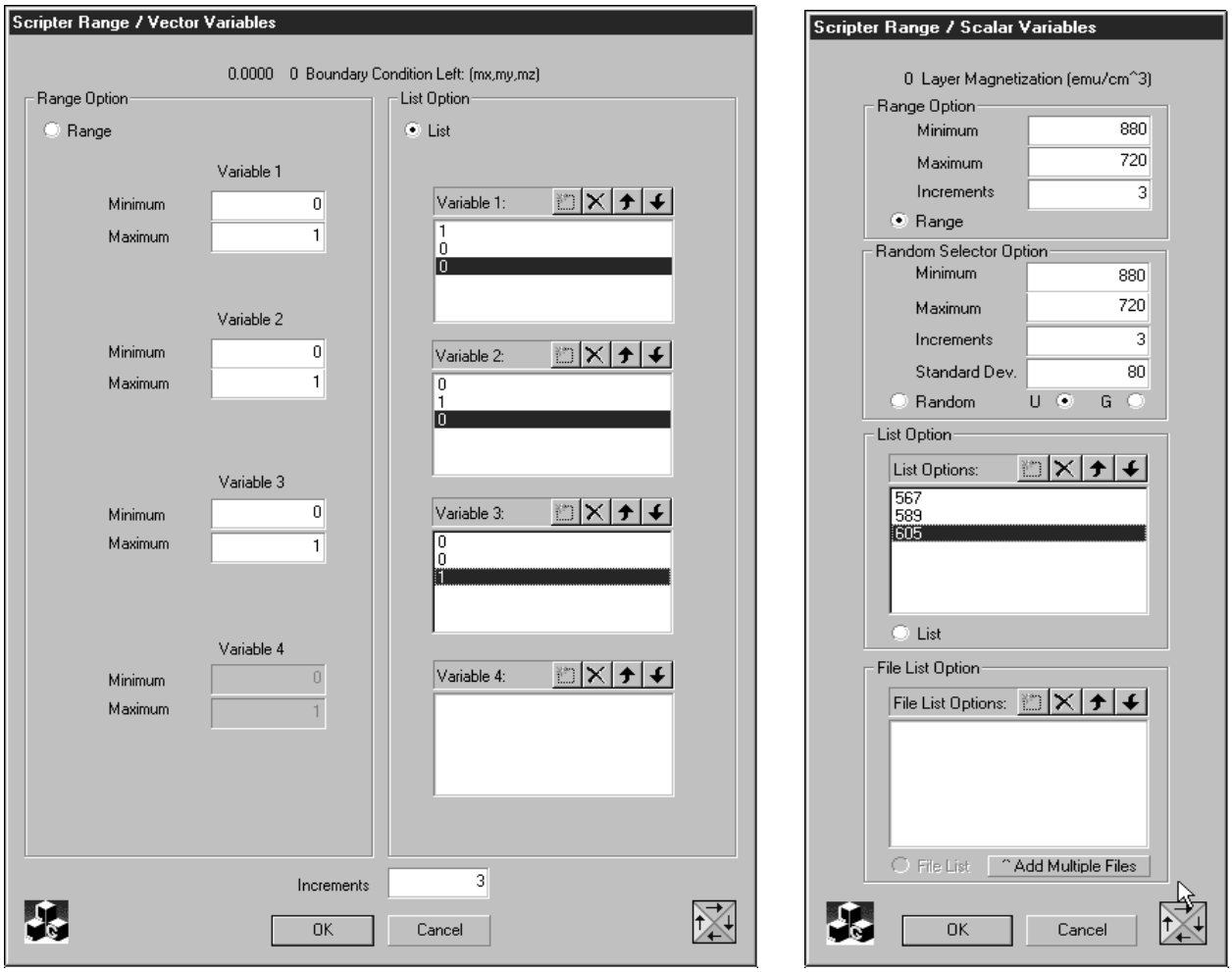


FIGURE 116. Scripting Range Vector and Scalar Menus

For single data values, each data entry prompt allows you to specify:

1. A Range
2. A Random Selector
3. A list of values, or
4. A file should you wish to loop on this as a variable.

LLG asks for the minimum, maximum and increment number for the variation of that parameter for the range option. In the example above, the Saturation magnetization will step from 700, 725, 750, 775, and 800, that is, from 700 to 800 in 5 values. For the random option, you must enter the minimum, maximum, standard deviation, number of increments and the type of random variable to use, either gaussian or uniform. If you use uniform variates, the range is from min->max. If you choose gaussian deviates, the mean is (max+min)/2 and the standard deviation is as specified. The list option allows you to enter any (appropriate) list of values. The file option, when enabled, allows you to scan for files. Use the **Multiple** add button at the bottom to add more than one file at a time from a directory of your selection. When you check vector (multiple) values you are prompted to enter them in either range or list format only. Once the sequence is complete, LLG creates a new directory. The name of the directory is the seed file's name augmented by the date and time. The files will be created in the new directory and will have the same file name as the original file, augmented by a number 0, 1... and so on. Since the directory names are keyed to seconds, you will never be in danger of overwriting your files. LLG will also write the appropriate batch file in the newly created directory. If your param file uses any auxiliary files (as discussed above), then the same files will be used in each parameter variation file. Presently, you must specify position dependent files and mask files independently from the batch process (it is not practical to have 100,000 parameters to vary). LLG will also write a new title containing the original file name and the problem variance number, as well as specify which parameters are being varied in comments 5-10 (see Notes/IO above).

Batch Mode Position Dependent Parameters

There is a protocol for using batch mode computations using shaped boundaries and position dependent parameters, and this procedure is summarized here in the order in which is must be implemented.

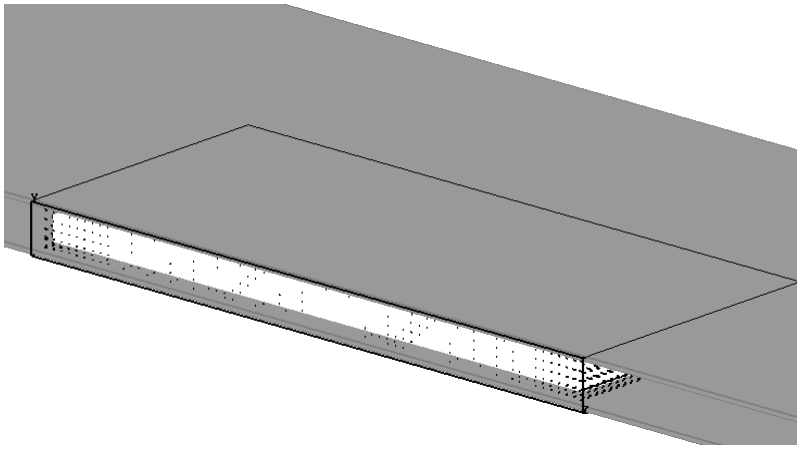
1. Make the appropriate *.llg_param file and store it.
2. Go back to the mask editor and make the appropriate *.llg_mask file and store it.
3. Go to the position dependent parameters sheet and make and edge for shaped boundaries and activate it. You will see now that additional cells have been turned on.
4. Store the *.llg_position file.
5. Store the *.llg_shape file.
6. Go back to the mask editor and store the new *.llg_mask file with the corrected number of cells activated. I usually overwrite the old mask.
7. Go to the batch page and check the mask, position dependent parameters and shape file check boxes. Load the appropriate file-names into the fields provided.
8. Resave your *.llg_param file.
9. You can now make variations on this llg_param file if you choose.
10. Use the scripter to make a batch file with all of your *.llg_param files included.
11. Run your batch mode problems. Note that having the check boxes checked in the batch page does not effect problems run interactively.

Closing the Scripting Interface

Click the **Close Scripter** button to close the scripting interface.

CHAPTER 24

Viewing Files



The **File Viewer** is a simple file-viewing utility. You activate the **View Sheet** by clicking the **Domain View**er icon at the top of the screen. With the file-viewing utility, you can load one of four standard LLG files:

- An *.llg_dom file that contains direction cosines.

  To display a file containing direction cosines, click the **Direction Cosines (Angles)** button and then click the **Load File** button. You make make an MFM image of this file by checking the appropriate MFM mode and clicking on **Compute**. You may also form the difference between two **Direction Cosines (Angles)** files.
- An *.llg_mask file that contains the position-dependent mask file.

  Select a mask file (**Mask or Hysteresis Mask**) by selecting the appropriate button.
- Any LLG file that contains a vector field.

  Select a **3D Vector Field** file by selecting the appropriate button.
- An *.llg_hyspart file where 3D dynamical data can be viewed (see the Movie Page on methods for creating *.llg_hyspart files). Since the *.llg_hyspart file contains up to three masked projections of magnetization, the loading sequence requires you to define the region of interest (1st, 2nd or 3rd). A three dimensional projection from an llg_hyspart file is shown below for a single Fe moment relaxing in a 5kOe field.

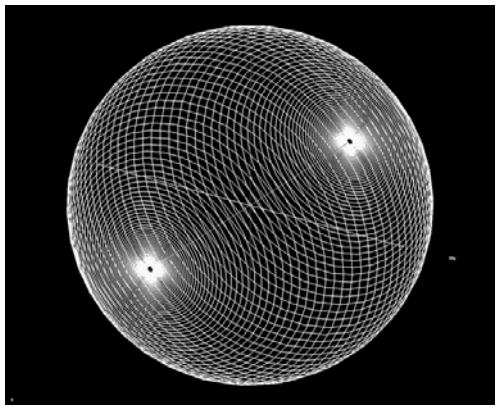


FIGURE 117. Dynamical Data View

The viewing option is useful for analyzing files that you might use as initial conditions or use to interpolate onto a new grid.

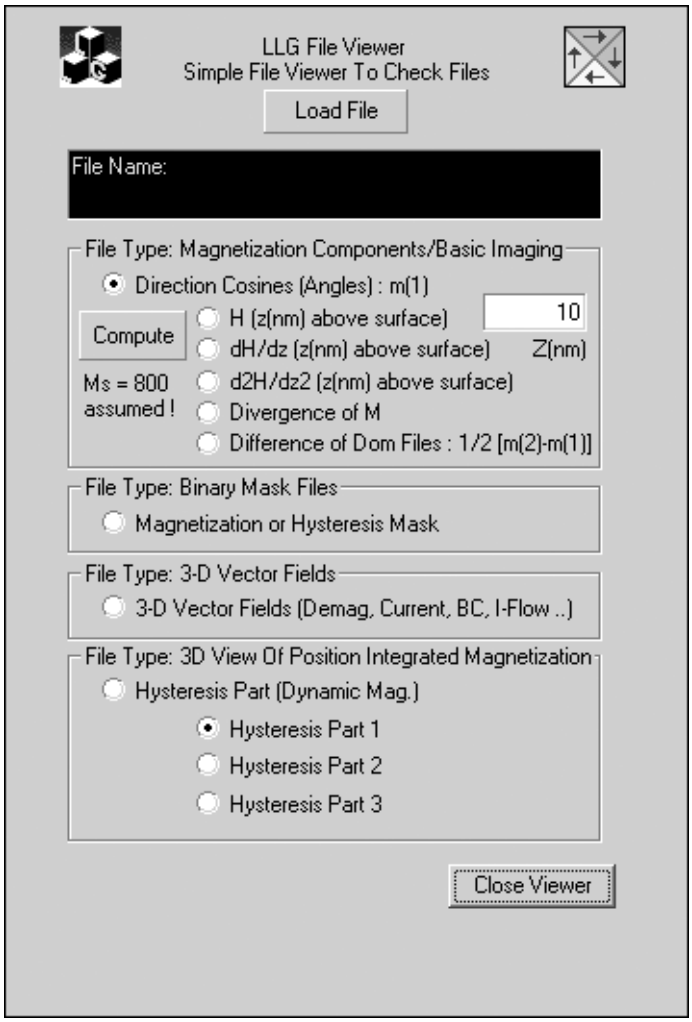
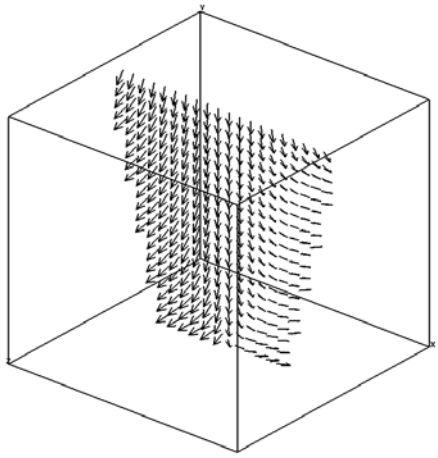


FIGURE 118. LLG File Viewer

CHAPTER 25

Viewing Movies



Once a simulation is complete, you can review the results through the **Movie Sheet**. Just load a movie file and play it! LLG's movies are not just graphics files; they contain all of the data stored in binary format. LLG renders the data in the form of an animated sequence that is termed a movie. You can adjust how the movie is rendered at any time with the **Graphics Sheet** at the bottom-left of the screen. Refer to the Chapter 5-LLG Environment for details on graphics.

LLG Movie Player Sheet - Movie Page

Click the **Movie Viewer** icon in the tool bar at the top of the screen to activate the **Movie Player**.

Loading and Saving Options

Click the **Load Movie** button to load a movie from a file. You will be prompted for the *.llg_param file that was used to create the movie. The LLG v2 Movie Viewer will read and display LLG v1 and v2 movies.

Click the **SaveDom** button to save an ASCII *.llg_dom file. You can access your binary data that is stored in a movie file and save any frame to an ASCII file. This file can be used to seed an initial condition for another LLG simulation or as input to a program that you might write to process, interpret or present data based on magnetization cosines. The file format is given in Chapter 4-Loading/Saving Files.

AVI Files

With LLG, you can create and save a Windows video stream movie *.avi file from your LLG movie. These standard Windows avi files can be viewed by any standard windows video-viewing utility. LLG is distributed with a simple utility named **LLGAviMoviePlayer.exe**. You can distribute this movie-viewing utility free to your colleagues with the movies. This allows you to circulate your results through avi files with those who do not have LLG Micromagnetics Simulator.

Load your movie and position the view how you want to display the scene. The avi movie contains no data. The avi file is composed of compressed bitmap images in a video stream (riff file). Once you are ready to create the avi file, click the **Save AVI** button. You will be prompted to save a compressed movie. Microsoft Video compression at a quality factor of 50% is recommended. (One bitmap image at normal display size occupies 1.7MB of memory and a movie with 41 frames requires over 68MB of disk space!) Click the **OK** button to proceed. You will be prompted to select the compression method and compression quality.

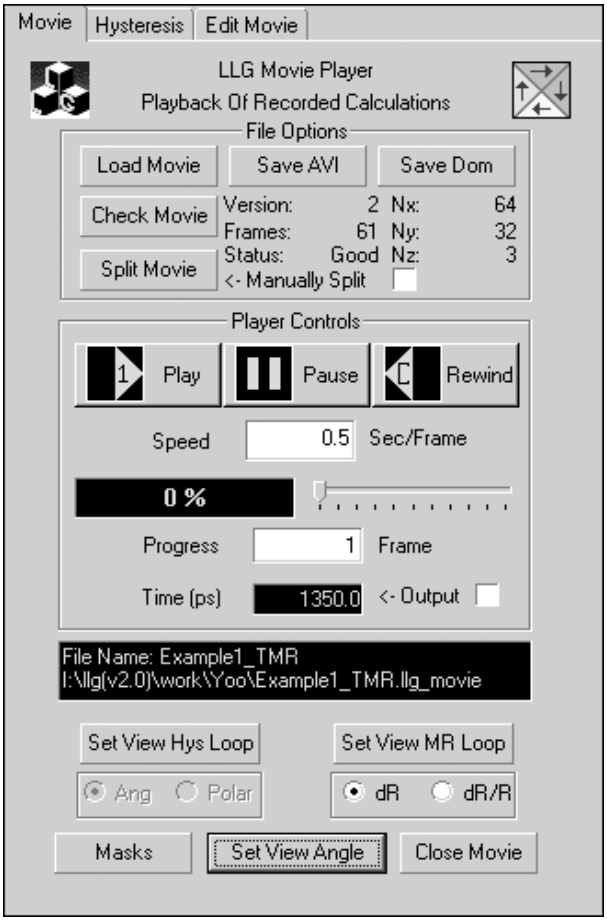


FIGURE 119. Movie Player Sheet - Movie Player Page

MOVIE VIEWING OPTIONS

- You can choose several viewing options through the **Movie Player**.
- The right facing triangle **Play**s a movie from the beginning to the end.
- The square is the **Stop** button.
- The double lines are the **Pause** button.
- To control the speed, enter the length of time you want each frame to run in the **Speed** edit box. The default is .10 second/frame.
- Use the **Frame** slide bar or edit box to set the movie's frame manually.
- The **Progress** edit box tracks the percentage of the movie that has been played. This provides you with information on the number and progress of frames in a movie.

MR AND HYSTERESIS LOOPS

You can recursively divide the OGL screen for multiple views of your data.

- For data sequences that include hysteresis loops or MR loops that are embedded in the movie, use the **Set View Hys Loop** and **Set View MR Loop** buttons to activate the appropriate loop in the active (clicked) OGL View.
- Click the **Set View Angle** button to return the view back to the direction cosines of the magnetization, which is the default.
- If the hysteresis loop is rotational, you can click the **Ang** or **Polar** button to define the display the polar loop.
- If you have computed an MR Loop, you can display the data as the change in resistance (**dR**) or the normalized change in resistance (**dR/R**), by clicking the appropriate button.

INTERACTING WITH THE DATA

Once a movie has finished playing or while a movie is paused, you can interact with data through the **Selection Page**, as described in Chapter 5-LLG Environment. Click the **Close Movie** button to end a movie session cleanly. You need not exit the Movie Viewer to view additional movies. To view a new movie, just load a new one.

EDITING OR CREATING MASKS

Click the **Masks** button to edit or create masks (page 139). This is useful for preparing masks for the move-hysteresis utilities.

SPLITTING A MOVIE

Somtimes movies grow beyond your physical memory limit. LLG has two mechanisms to split movies. By pressing the **Split Movie** button LLG will automatically (try to) split a movie. There have been some problems in splitting movies that were too large for the memory of your machine, especially when the exit from the simulation was not done correctly. You must click the **Close All** button when a simulation is complete in order to write the correct frame number in the movie file. By checking the **Manual** box, you activate the manual movie splitter where you can enter the frame count of the movie file and LLG will split that file into two (nearly) equally sized files (without bombing). The equation used to estimate the number of frames is given on the dialog page.

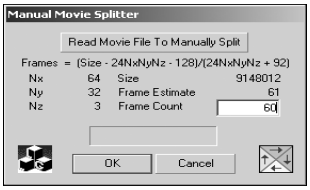

Manual Movie Splitter
Read Movie File To Manually Split
Frames = (Size - 24NxNyNz - 128)/(24NxNyNz + 92)
Nx 64 Size 9148012
Ny 32 Frame Estimate 61
Nz 3 Frame Count 60
OK
Cancel

FIGURE 120. Manual movie splitter.

MOVIE PLAYER - EXTRACT HYSTERESIS LOOPS PAGE

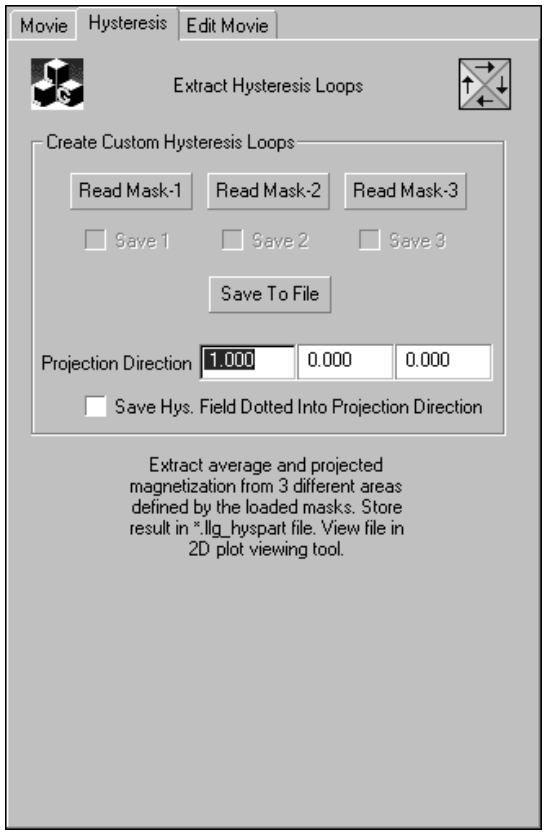


FIGURE 121. Movie Player Sheet- Extract Hysteresis Loops Page

The **Extract Hysteresis Loops Page** is for extracting data from a movie file. Unlike normal LLG simulation data, hysteresis data that are extracted from a movie use direction cosines only, that is, the magnitude of the magnetization associated with each spin is ***NOT*** retained. (It ***IS*** retained for computing the hysteresis loops stored in the *.llg _hys files and in the movie file in the hysteresis loop itself.) When you click the **Hysteresis** tab, a mask view OGL window appears.

- You can load up to three masks with the **Read Mask** buttons from which the region of interest to extract three hysteresis loop can be specified. Select the projection direction to specify that component of the field and magnetization to write to the file.
- Check the **Save Hys Field Dotted Into Projection Direction** box to save a particular field value to file. If you do not, then the original hysteresis fields will be written to the file. Remember to check the appropriate boxes to indicate which loops you want to save to the *.llg_hyspart file.
- Click the **Save To File** button to store your hysteresis loops. You can examine your *.llg_hyspart file with the 2D Graphics utilities (see page 31).

MOVIE PLAYER - EDIT MOVIE FILE PAGE

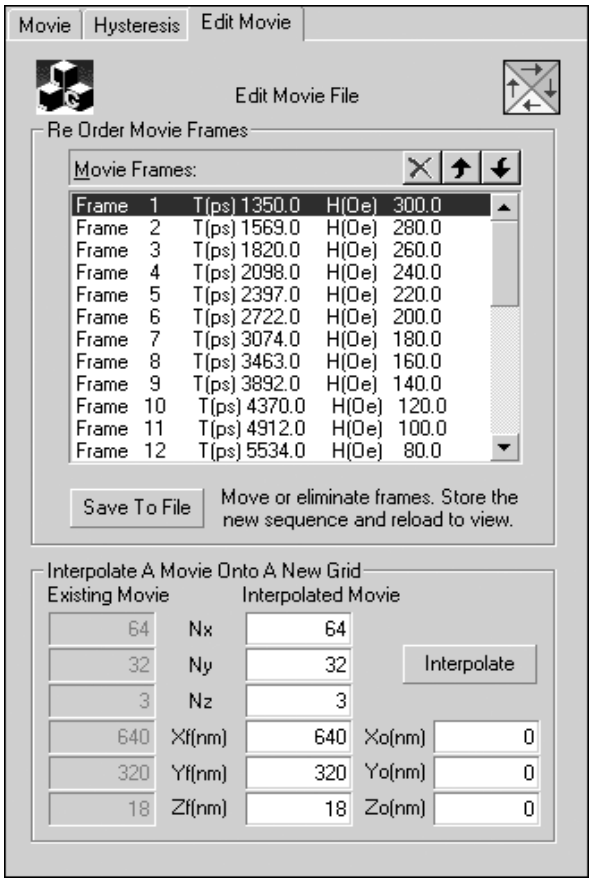

Movie
Hysteresis
Edit Movie
Edit Movie File
Re Order Movie Frames
Movie Frames:
Frame 1 T(ps) 1350.0 H(Oe) 300.0
Frame 2 T(ps) 1569.0 H(Oe) 280.0
Frame 3 T(ps) 1820.0 H(Oe) 260.0
Frame 4 T(ps) 2098.0 H(Oe) 240.0
Frame 5 T(ps) 2397.0 H(Oe) 220.0
Frame 6 T(ps) 2722.0 H(Oe) 200.0
Frame 7 T(ps) 3074.0 H(Oe) 180.0
Frame 8 T(ps) 3463.0 H(Oe) 160.0
Frame 9 T(ps) 3892.0 H(Oe) 140.0
Frame 10 T(ps) 4370.0 H(Oe) 120.0
Frame 11 T(ps) 4912.0 H(Oe) 100.0
Frame 12 T(ps) 5534.0 H(Oe) 80.0
Save To File
Move or eliminate frames. Store the new sequence and reload to view.
Interpolate A Movie Onto A New Grid
Existing Movie
Interpolated Movie
64 Nx 64
32 Ny 32
Interpolate
3 Nz 3
640 Xf(nm) 640 Xo(nm) 0
320 Yf(nm) 320 Yo(nm) 0
18 Zf(nm) 18 Zo(nm) 0

FIGURE 122. Movie Viewer Sheet - Edit Movie File Page

The **Edit Movie File Page** is for editing and storing LLG movie files. You can reorder or move movie frames. Once you have revised or edited a movie, click the **Save To File** button to store it as a standard LLG movie.

INTERPOLATING A MOVIE

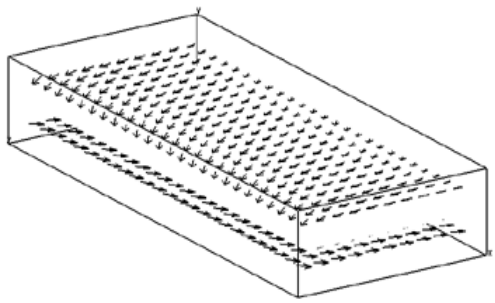
With LLG, you can interpolate an existing movie onto a new grid. You can refine the grid or coarsen the grid. Also, you can extract a piece of the structure in an existing movie and make that piece into a new movie.

- The size and grid density of the existing movie are shown in the edit boxes to the left.
- Specify the new grid density in the active Nx, Ny and Nz edit boxes.
- Extract a piece of the existing movie by specifying the region in the following edit fields:,
  - Xf (nm) right side
  - Xo(nm) left side
  - Yf (nm) back side
  - Yo(nm) front side
  - Zf (nm) top side
  - Zo(nm) bottom side

IMPORTANT NOTE: Clicking the **Interpolate** button prompts you for a file name for the new movie. If you do not choose a new file name, you risk overwriting your data.

CHAPTER 26

Sample Problem 1-Basic Data Input for a Permalloy Cube



This is the simplest of all problems to run. The structure is a single material and contains no boundary conditions, external fields or sources of any kind. It can be initiated by entering the size and discretization of the structure in the LLG Input Sheet-Main Page. For all other features, use the default. (**NOTE**: Your LLG CD contains all sample problems in the Sample Files subdirectory within LLG's installation directory. The prefix for each sample file is **Sample #**.)

INPUT SHEET - MAIN PAGE

1. Initiate an LLG calculation by clicking the **New** button on the **Tool Bar** to activate the **Main Page**.
2. Enter the **Simulation Volume** with the slide bars or edit boxes: 56 nm each for X(nm), Y(nm) and Z(nm).
3. In the adjacent discretization boxes, enter 7 sub-elements each for N_x, N_y and N_z.

INPUT SHEET - GLOBALS PAGE AND MATERIALS PAGE

1. Click the **Globals** tab.
2. Select **U** (Uniaxial) in the **Anisotropy Type** group box. The uniaxial anisotropy edit field ($\mathbf{K}_u$) should be enabled and the cubic anisotropy ($\mathbf{K}_c$) edit field should be disabled.
3. Click the **Material Selector** button, which activates the **Materials Page**.
4. Select **Permalloy** from the **Precoded Materials and Properties** section, which loads Permalloy's parameters into the database fields.
5. Click **Accept**. This closes the Materials Page, returns you to the Globals Page, loads the parameters for Permalloy into the edit fields in the **Globals Page**, and records "Permalloy" after "Properties Of".
6. Click the **Accept Changes** button, which exits you to the **Main Page** and loads "Permalloy" into the edit field at the top.

INPUT SHEET - COMPUTATION PAGE

1. Click the **Computation** tab.
2. Click the **Energy (Slower)** button. Make sure that the **Iterations** and **Convergence** boxes are selected. Be sure that the **Convergence** criteria is set to 0.0001 and that the number of **Iterations** is 25000.
3. Click **Accept Changes,** which exits you to the **Main Page**.

INPUT SHEET - INITIALIZE PAGE

1. Click the **Initialize** tab.
2. Click the **Vortex Z-Plane** button.
3. Click **Accept Changes,** which exits you to the **Main Page**. You can save your input configuration to a file by clicking the **Save v2 Input** button.
4. Click the **Begin Simulation** button.

SAVING FILES

If you have not saved the new input parameters, LLG will prompt you to do so. If you respond yes, you will be prompted a second time for the name of the input file (*.llg_param). By default, the program will create two more files: a domain file with the direction cosines on output (*.llg_dom) and a convergence file with iteration histories and energy values (*.llg_conv). Each file will have the prefix of your *.llg_param filename. If you select ***NOT*** to save the input parameter file, LLG will prompt you to enter *.llg_dom and *.llg_conv filenames. If you select ***NOT*** to enter filenames, LLG automatically creates the two files in your running default directory and names them untitled.llg_dom and untitled.llg_conv. Once files have been specified, a progress meter at the bottom left tracks the computation of the demagnetization field coupling tensor.

SIMULATION SHEET - SIMULATION PAGE

Once the coupling tensor has been computed, the LLG Simulation Sheet appears.

1. Click **Surface 3D Graph Type** to see a three-dimensional view of the Fe cube.
2. Click the **Arrow** button under **3D Objects** to see the surface magnetization on the whole cube.
3. Click the **Start To Compute** button, which initiates LLG to relax the magnetization. The meter tracks the simulation's progress as a percentage of the maximum number of iterations and updates the iteration count. The in-plane flux vortex will degenerate so that the magnetization points perpendicular to the plane of the vortex in the core in about 200 iterations. LLG will stop the calculation once the convergence limit (0.0001 in this case) has been reached.

SIMULATION SHEET - VIEWS PAGE

Experiment with visualizing different parts of your structure.

1. Click the **Orient** tab; then, click the **Z-Slice** button.
2. Click the **Modes** tab; then, select **Bitmap Graph Type**. In the middle bitmap pane, the vortex is visualized as the central core in the Z-component of the magnetization.
3. To examine the bitmap, use the **Orient Slice** slide bar at the bottom left of the screen to scroll through the slices. The helicity in the flux closure pattern can be seen as an asymmetry in the magnetization pattern.
4. Select the **Modes Contour Graph Type**; then, scroll through the slices again. Then, examine the components of the effective field. Select **3-D Arrows** to see the surface fields on the whole cube and select the **Effective Field** from the **Simulation Sheet-Views Page**. Notice that the magnetization is indeed along the effective field direction.
5. Click the **Selector** tab. Then, click on any arrow in the OpenGL window. The values of the magnetization, effective field, residual and energy density appear in the edit boxes at the bottom (the Selector tool must be directly over a point). When you Pause LLG, you can examine the numbers this way at any time during the simulation.
6. Select the **Residuals (Change/Iteration)** from the **Views Page**. You will see the latest update on the residual pattern. Select the **Demagnetization Field** to see the demagnetization field. If you like, use the **Selector** to examine the numbers.

COMMENTS

Notice that the sub-element size was specified to be 8 nm. This is near the upper limit that yields converged solutions.

Unstable Problems

Try rerunning this sample with 6 sub-elements per side, which will make the problem unstable with the 1-Pt minimization method. The instability is a result of setting the sub-element size too large. When the simulation begins, the moments will oscillate back and forth and, in the worst case, the residuals displayed in the LLG Simulation Control will near 2.0. This is a pathological situation. If a simulation enters this regime, ***STOP THE PROBLEM IMMEDIATELY AND RE-INITIATE IT ON A FINER GRID***! Test the residuals when you are running any calculation for the first time. If you notice the characteristic red and blue stripes in the **Bitmap Mode** of the **Residual (Change/Iteration) View Option**, decrease the time step (for parallel algorithms). If that does not work, stop and refine your grid.

Since the Save button was checked on the Main Page, the convergence output file for this example includes a complete iteration history.

FEATURES

Structure: 56 nm x 56 nm x 56 nm

Sub-Element: 8 nm x 8 nm x 8 nm

Discretization: 7 x 7 x 7

Material: Permalloy

Relaxation: 1-Pt Energy Minimization

Initialization: Vortex in Z-Plane

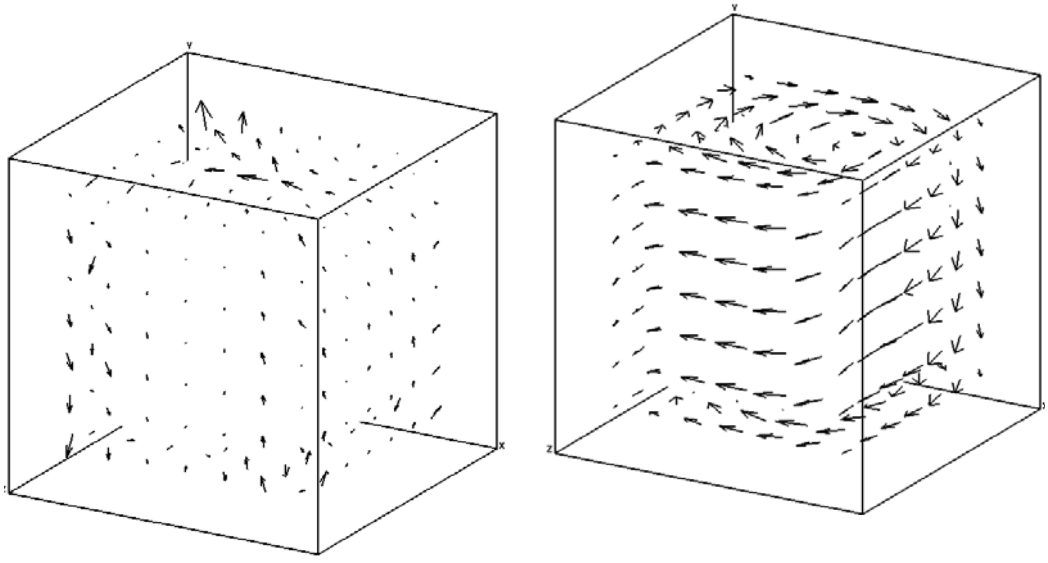


FIGURE 123. Surface Magnetization/Effective Field in 3D Arrows and Change Pattern in 3D Arrows

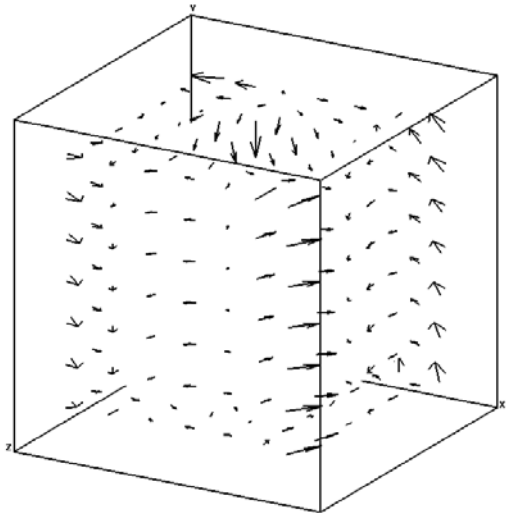
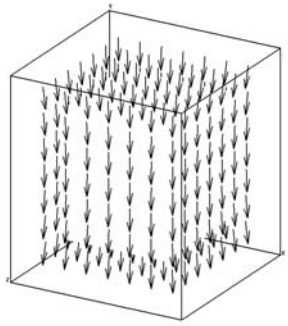


FIGURE 124. Demagnetization Field Pattern in 3D Arrows

CHAPTER 27

Sample Problem 2-Basic Data Input for a Soft Magnetic Cube



This problem is a continuation of Sample Problem 1. It presents results for a single material with no boundary conditions, external fields or sources of any kind. This sample problem can be initiated by entering the size and discretization of the structure in the **Input Sheet-Main Page**. For all other features, run this example exactly as Sample 1, except set the magnetization in the **Globals Page** to 400 emu/cm^3.

COMMENTS

Since the Save button was checked on the **Main Page**, the convergence output file for this example includes a complete iteration history.

FEATURES

Structure:	56 nm x 56 nm x 56 nm
Sub-Element:	8 nm x 8 nm x 8 nm
Discretization:	7 x 7 x 7
Material:	Permalloy exchange and anisotropy, M_s = 400 emu/cm^3
Relaxation:	1-Pt Energy Minimization
Initialization:	Vortex in Z-Plane

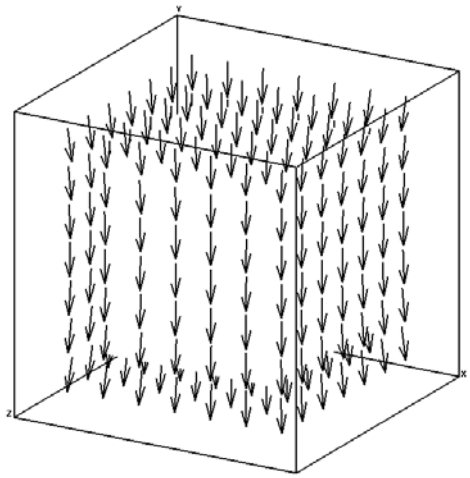
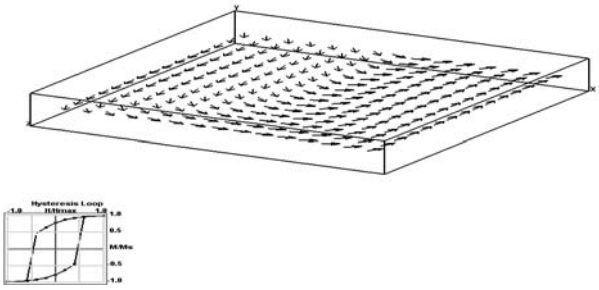


FIGURE 125. Surface Magnetization (and Effective Field) Pattern in 3D Arrows Mode

CHAPTER 28

Sample Problem 3-Uniform Hysteresis Loop for a Magnetic Platelet



This sample problem is of modest complexity. The simulation requires a volume to be descretized, a single material property to be set and a uniform hysteresis loop to be specified. This is the simplest of all hysteresis loop problems.

INPUT SHEET - MAIN PAGE

1. Initiate an LLG calculation by clicking the **New** button on the **Tool Bar** to activate the **Main Page**.
2. Enter the **Simulation Volume**: 150 nm for X(nm), 150 nm for Y(nm) and 10 nm for Z(nm).
3. In the adjacent discretization boxes, enter 15 sub-elements for N_x, 15 for N_y and 1 for N_z.

INPUT SHEET - GLOBALS PAGE AND MATERIALS PAGE

1. Click the **Globals** tab.
2. Select **U** (Uniaxial) in the **Anisotropy Type** group box. The uniaxial anisotropy edit field ($\mathbf{K_u}$) should be enabled and the **C** (Cubic) anisotropy ($\mathbf{K_c}$) edit field should be disabled.
3. Click the **Material Selector** button, which activates the **Materials Page**.
4. Select **Permalloy** from the **Precoded Materials and Properties** section, which loads Permalloy's parameters into the database fields.
5. Click **Accept**. This returns you to the Globals Page, loads the parameters Permalloy into the edit fields in the Globals Page, and records "Permalloy" after "Properties Of".
6. Click the **Accept Changes** button, which exits you to the **Main Page** and loads "Permalloy" into the edit field at the top.

INPUT SHEET - COMPUTATION PAGE

1. Click the **Computation** tab.
2. Select **Energy (Slower)**.
3. Click **Accept Changes** to exit this page.

INPUT SHEET - INITIALIZE PAGE

1. Click the **Initialize** tab.
2. Select **Uniform X-Direction**.
3. Click **Accept Changes** to exit this page. No other modifications to the default settings are required to run this problem.

INPUT SHEET - HYSTERESIS-U PAGE

1. Click the **Hys-U** tab.
2. Click the **Uniform** box to activate the uniform hysteresis option. Using the slide bar or the edit box, set the field in the X-direction **Hx(Oe)** to **1000 Oe**.
3. Enter **11** into the **# Points** field. Since an odd number of field points was selected for a single hysteresis loop field sweep (Max→Min), the zero-field magnetization will be computed. The field values will be displayed in the OpenGL window. Refer to the legend toward the right of the OpenGL window for the color coding. The triangular waveform is indicative of a linear field sweep.
4. Enter **1.00**, **0.00** and **0.00** for the **Loop Direction <x,y,z>** for the projection axis for the hysteresis loop display. Since there is only an X-component, the magnetization is dotted into a unit vector along X for the hysteresis display.
5. Click **Accept Changes** to complete the hysteresis specification.
6. Click **Begin Simulation.**

SAVING FILES

If you have not saved the new input parameters, LLG will prompt you to do so. If you respond yes, you will be prompted a second time to name the input file (*.llg_param).

By default the program will create three more files: a domain file with the direction cosines on output (*.llg_dom), a convergence file with iteration histories and energy values (*.llg_conv), and a hysteresis output file (*.llg_hys) with the magnetization directions and field directions recorded at every field point. Each file will use the prefix of your *.llg_param filename. If you select NOT to save the input parameter file, LLG will prompt you to enter *.llg_dom, *.llg_conv and *.llg_hys filenames. If you select NOT to enter filenames, LLG automatically creates and names the three files in your running default directory: untiitled.llg_dom, untitled.llg_conv and untitled.llg_hys. Once files have been specified, a progress meter at the bottom left tracks the computation of the demagnetization field coupling tensor.

SIMULATION SHEET AND OGL PROPERTIES SHEET

Then, the **Simulation Sheet** appears, along with a top-down view of your Permalloy platelet. Select the **Modes** tab under **OGL Properties Sheet**. Select the **Arrow Graph Type** to see the surface magnetization on the platelet.

VIEWING THE HYSTERESIS LOOP

1. Right click on the OGL window and select **Split Window Horizontally**.
2. Decrease the size of the top half of the window by sliding the splitter window bar upward.
3. Click the **Views** tab to reveal the view menu options.
4. Left click on the upper pane of the OGL window; view number 1 should appear at the top of the **Views Page** after "**Active View =**." Then, click **Hysteresis Loop** on the **Views Page**. Your loop axes should be visible on top.
5. Right click on the lower window pane and select **Split Window Vertically**. Left click on the lower right window; view number 3 should appear at the top of the **Views Page** after "**Active View =**."
6. Click the **Bitmap** button in the **OGL Props Sheet-Modes Page.**

You should have a bitmap view at bottom right, an arrow view at bottom left and a hysteresis view at the top. You can change the view options and the graphical representation of your data in each window. To remove a view, right click on the pane and select **Delete Active View**.

Start the LLG computation by clicking the **Start To Compute** button. The meter tracks the simulation's progress as a percentage of the number of hysteresis loop points and updates the iteration count. The domain pattern changes as the field is swept and the hysteresis loop is updated. If you pause the computation, you can determine the numerical value of the parameters. Click the **Selector** tab; then, click the **Arrays** tab. Click the **Activate Picker** box. Also, you can click on points in the hysteresis loop to ascertain their values.

COMMENTS

Notice that the sub-element size was specified to be 10 nm. This is near the upper limit that yields converged solutions for Permalloy. Try rerunning this sample with 12 sub-elements per side, which makes the problem unstable with the 1-Pt. minimization method. The instability is a result of setting the sub-element size too large. When the simulation begins, the moments will oscillate back and forth and, in the worst case, the residuals displayed in the **Simulation Page** will near 2.0. This is a pathological situation. If a simulation enters this regime, STOP THE PROBLEM IMMEDIATELY AND RE-INITIATE IT ON A FINER GRID!

Test your residuals when running any calculation for the first time. If you notice the characteristic red and blue stripes in the **Bitmap Graph Type** of the **Residual (Changes/Iteration) View Option,** decrease the time step (for parallel algorithms). If that doesn't work, stop and refine your grid. Also, note how high the convergence parameter is set. This high a value will only work on extremely small problems, such as this one, and then not always accurately. Try this problem again, set the convergence exit criteria to 0.0001 and observe the differences in the solutions. Since the **Save** button was checked on the **Main Page**, the convergence output file for this example includes a complete iteration history.

FEATURES

Structure: 150 nm x 150 nm x 10 nm

Sub-Element: 10 nm x 10 nm x 10 nm

Discretization: 15 x 15 x 1

Material: Permalloy

Relaxation: 1-Pt Energy Minimization

Initialization: Uniform in X

Hysteresis: Uniform, H_x = 1000 Oe, N_{pts} = 11

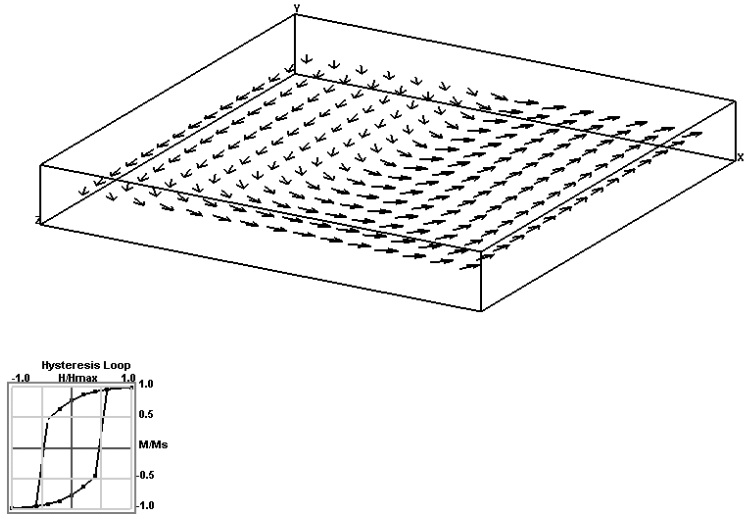
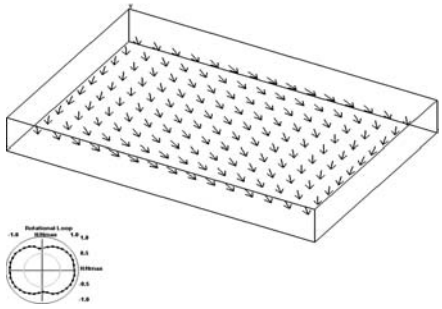


FIGURE 126. Surface Magnetization Pattern and Hysteresis Loop during Switching in 3D Arrows

CHAPTER 29

Sample Problem 4-Rotational Hysteresis Loop for a Magnetic Platelet



This sample problem is of modest complexity. In this simulation, a volume is descretized, a single material property is set and a uniform rotational hysteresis loop is specified.

INPUT SHEET - MAIN PAGE

1. Initiate an LLG calculation by clicking on the **New** icon in the tool bar.
2. Enter the **Simulation Volume** with the slide bars or edit boxes: 150 nm for X(nm), 100 nm for Y(nm) and 10 nm for Z(nm).
3. In the adjacent discretization boxes, enter 15 sub-elements for N_x, 1 for N_z and 10 for N_y.

INPUT SHEET - GLOBALS PAGE/MATERIALS PAGE

1. Click the **Globals** tab.
2. Select **U** (Uniaxial) in the **Anisotropy Type** group box. The uniaxial anisotropy edit field ($\mathbf{K_u}$) should be enabled and the **C** (Cubic) anisotropy ($\mathbf{K_c}$) edit field should be disabled.
3. Click the **Material Selector** button, which activates the **Materials Page**.
4. Select **Permalloy** from the **Precoded Materials and Properties** section, which loads **Permalloy**'s parameters into the database fields.
5. Click **Accept**. This returns you to the Globals Page, loads the parameters for Permalloy into the edit fields in the Globals Page, and records "Permalloy" after "Properties of".
6. Click the **Accept Changes** button, which exits you to the Main Page and loads "Permalloy" into the edit field at the top.

INPUT SHEET - INITIALIZE PAGE

1. Click the **Initialize** tab.
2. Click the **Uniform X-Direction**.
3. Enter **10.0** into the **Phi** edit field to cant the initial magnetization off the X-axis by 10^o.
4. Click **Accept Changes**.

INPUT SHEET - UNIFORM HYSTERESIS PAGE

1. Click the **Hys-U** tab.
2. Click the **Uniform** and **Rotational** boxes to accept a rotational hysteresis loop, and click the **X-Y Rotation Plane** button to select the plane of field rotation to be in the plane of the platelet.
3. Then, using the slide bar or the edit box, set the field in the **X-direction** H_x(Oe) in the **Maximum External Field** section to **300 Oe**.
4. Use the slide bar or edit box to set the **# Points** to **37**. This ensures that the rotation-field magnetization will be computed in ten-degree increments, including 0^o and 360^o. The field values will be displayed in the OpenGL window. Refer to the legend toward the right of the OpenGL window for the color-coding. The cosine (sine) waveform is indicative of a rotational field sweep.
5. Click the **3D Field View** button. This plots the field in 3D in a circle about the origin, where each point signifies the tip of the field vector during the rotational sweep. The direction for the magnetization component in the polar hysteresis loop display is always along the direction of the field. The polar output displays the magnitude of the magnetization along the field as the radius as a function of the angle of the field. You can toggle the view during the simulation to see the magnetization as a function of the field angle in a strip chart as well.
6. Click **Accept Changes** to complete the hysteresis specification, which returns you to the Main Page. No other modifications to the default settings are required to run this problem.
7. Click the **Begin Simulation** button. If you have not saved the new input parameters, LLG will prompt you to do so. Respond as in Samples 1, 2 and 3.

SIMULATION SHEET - SIMULATION PAGE

The **Simulation Sheet-Simulation Page** is activated and a top-down view of your Permalloy platelet appears on the screen.

1. Select the **Arrow Graph Type** to see the surface magnetization on the platelet surface.
2. Click the **Views** tab. Right click on the OGL window and select **Split Window Horizontally**. Left click on the upper pane of the OGL window; view number 1 should appear at the top of the **Views Page** after "**Active View =**." Then, click **Hysteresis Loop**. Your loop axes should be visible on top.
3. Click the **Start To Compute** button, which initiates LLG to relax the magnetization. Set up your OGL window as described in the previous example. LLG will start the computation. The meter tracks the simulation's progress as a percentage of the hysteresis loop points and updates the iteration count. The domain pattern changes as the field is swept and the hysteresis loop is updated.
4. Click the **Views** tab. The **View Polar** button allows you to toggle between the polar and angular views. When selected, the button reads **Angular** and the data is plotted as a function of angle as a strip chart. Click the button again to return to the **Polar** view.
5. Click the **Pause Computation** button, which allows you to use the **Arrays** feature of the **Selector** for exploring the numerical values of the parameters. Also, you can click on points in the polar hysteresis loop to identify their values. Notice that, when you pause the computation, the hysteresis and magnetization status bar at the bottom of the OpenGL window is updated with the values of the magnetization and field at the current hysteresis field point. Note that these values are updated only during idle time and not while the computational engine is running the simulation.

COMMENTS

Notice the pinched shape of the rotational hysteresis loop, as well as the slight asymmetry near 90^o and 270^o. Observe the change in shape of the rotational hysteresis loop when you increase the value of the Anisotropy or make the structure longer (increase the shape anisotropy).

FEATURES

Structure: 150 nm x 100 nm x 10 nm

Sub-Element: 10 nm x 10 nm x 10 nm

Discretization: 15 x 10 x 1

Material: Permalloy

Relaxation: 1-Pt Energy Minimization

Initialization: Uniform 10^0 from X in X-Z Plane

Hysteresis: Uniform, Rotational, H_x = 300 Oe, N_{pts} = 37

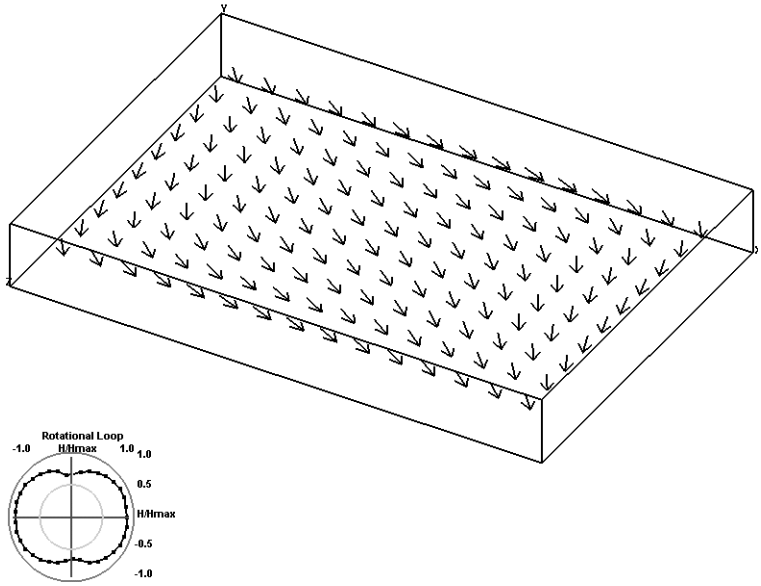
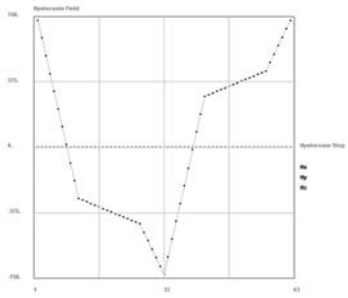


FIGURE 127. Surface Magnetization Pattern and Polar Hysteresis Loop during Switching in 3D Arrows

CHAPTER 30

Sample Problem 5-Non-uniform Hysteresis Loop for a Platelet



This sample problem is of modest complexity. In this simulation, a volume is descretized, a single material property is set and a non-uniform hysteresis loop is specified. The flexibility provided by the non-uniform hysteresis mode allows you to take advantage of the fact that the magnetization changes quickly as a function of the applied field near the coercive field, while it changes slowly elsewhere; therefore, tuning the number of hysteresis points appropriately saves computation time.

INPUT SHEET - MAIN PAGE

Initiate an LLG calculation. Use the same setup procedure and materials properties for Sample Problem 4. Except, set the **Simulation Volume** to 250 nm for X(nm), 100 nm for Y(nm), and 10 nm for Z(nm). In the adjacent discretization boxes, enter 25 sub-elements for N_x, 10 for N_y1 and for N_z.

INPUT SHEET - INITIALIZE PAGE

1. Click the **Initialize** tab.
2. Click the **Uniform X-Direction** button in the **3D Uniform Magnetization** field.
3. The **Sign On Uniform** options default to **Positive**, with Theta 90.0 (magnetization in the X-Z plane) and Phi 0.0 (magnetization along the X-axis). Enter **10.0** into the **Phi** edit field to cant the initial magnetization off the X-axis by 10^o. Close this page by clicking **Accept Changes**.

INPUT SHEET - NON-UNIFORM HYSTERESIS PAGE

1. Click the **Hys-NU** tab.
2. Click the **Non-Uniform** box to enable the section and to accept a non-uniform hysteresis loop. Then, you must specify an arbitrary, yet non-uniform, hysteresis loop. Then, design a field loop for a system where the coercive field is around 375 Oe.
3. The **Field Section Specified** edit box should read 1, the first field section. Enter **750.0** in the **Limit 1** edit field for **Hx**. Leave Hy and Hz set to zero. This is the initial field point for the first hysteresis field section.
4. Enter **-300.0** in the **Limit 2** edit field for **Hx**. Leave Hy and Hz set to zero. This is the final field point for the first hysteresis field section and, subsequently, the initial field point for section 2, should you select another field section.
5. Enter **10** in the **Number Of Field Points** edit box. This will interpolate 10 intervals between **Limit 1** and **Limit 2**. The first field section is the ONLY section that has n+1 points. Every other field section will have the specified number of points, n. (You must either add the extra point to the first section or the last; in LLG, it is in the first).

6. Then, click the **LOAD SECTION** button to enter the field section 1 into the hysteresis loop. If you do not, the field section will not be added to the hysteresis loop. This completes the specification for the first field section. **Sections Loaded** should indicate **1** and **Points Loaded** should indicate **11**.
7. Either use the arrows next to **Field Section Specified** to advance to section 2 or enter 2 into the edit box. Notice that LLG automatically records **Limit 2** from field section 1 in the **Limit 1** position for field section 2.
8. Enter **-450.0** in the **Limit 2** edit field for Hx. Leave Hy and Hz set to zero. This is the final field point for the second hysteresis field section and the initial field point for section 3.
9. Enter **15** in the **Number Of Field Points** edit box. Load the field section by clicking the **LOAD SECTION** button. Use this same process in entering the remaining fields.
10. Enter **3** into the **Field Section Specified** edit box. Enter **-750.0** in the **Limit 2** edit field for **Hx**. Enter **6** in the **Number Of Field Points** edit box. Load the field section by clicking the **LOAD SECTION** button.
11. Enter **4** into the **Field Section Specified** edit box. Enter **300.0** in the **Limit 2** edit field for **Hx**. Enter **10** in the **Number Of Field Points** edit box. Load the field section by clicking the **LOAD SECTION** button.
12. Enter **5** into the **Field Section Specified** edit box. Enter **450.0** in the **Limit 2** edit field for **Hx**. Enter **15** in the **Number Of Field Points** edit box. Load the field section by clicking the **LOAD SECTION** button.
13. Enter **6** into the **Field Section Specified** edit box. Enter **750.0** in the **Limit 2** edit field for **Hx**. Enter **6** in the **Number Of Field Points** edit box. Load the field section by clicking the **LOAD SECTION** button. The field view on the screen will appear in 2-D, as shown below.

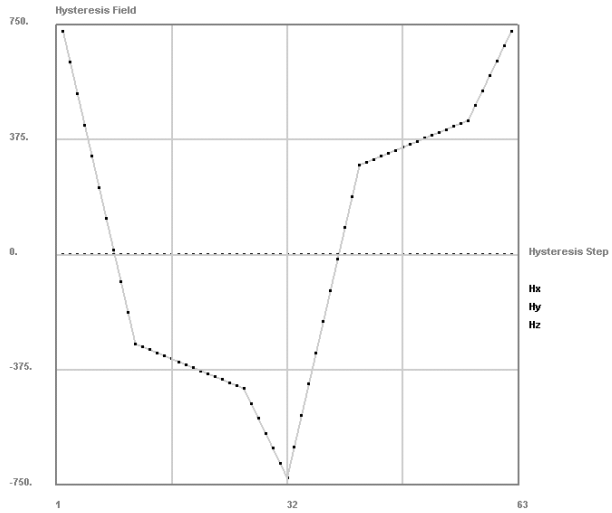


FIGURE 128. Non-uniform Hysteresis Loop 2D View for a System with a Coercive Field near 375 Oe

14. To save the specified field to an ASCII file, click the **Save Input File** button. You will prompted for a file name. To use this field profile for another problem, use the **Read Input File** button to read the file. It will automatically be loaded into the Non-Uniform Sampling Hysteresis Loop section for use in the LLG simple field editor and for visualization.
15. Choose **Accept Changes** to complete the hysteresis specification. No other modifications to the default settings are required to run this problem.
16. Click the **Begin Simulation** button. If you have not saved the new input parameters, LLG will prompt you to do so. Respond as in Samples 1 and 3. Set up your graphics windows as described in the prior two examples.

SIMULATION SHEET - SIMULATION PAGE

The **Simulation Sheet-Simulation Page** is activated and a top-down view of your Permalloy platelet appears on the screen.

1. Select the **Arrow Graph Type** to see the surface magnetization on the platelet surface.
2. Click the **Views** tab. Right click on the OGL window and select **Split Window Horizontally**. Left click on the upper pane of the OGL window; view number 1 should appear at the top of the Views Page after "**Active View =**." Then, click **Hysteresis Loop**. Your loop axes should be visible on top.
3. Click the **Start To Compute** button, which initiates LLG to relax the magnetization. The meter tracks the simulation's progress as a percentage of the number of hysteresis loop points and updates the iteration count. The domain pattern will change as the field is swept and the hysteresis loop is updated.
4. Click the **Selector** tab at the bottom of the screen, and then click the **Arrays** tab. Click the **Activate Picker** box, then click on a point in the polar hysteresis loop. The point's values appear in the fields.

COMMENTS

Notice the higher field density local to the coercive field in the hysteresis loop.

FEATURES

Structure: 250 nm x 100 nm x 10 nm

Sub-Element: 10 nm x 10 nm x 10 nm

Discretization: 25 x 10 x 1

Material: Permalloy

Relaxation: 1-Pt Energy Minimization

Initialization: Uniform 10^0 from X in X-Y Plane

Hysteresis: Non-Uniform

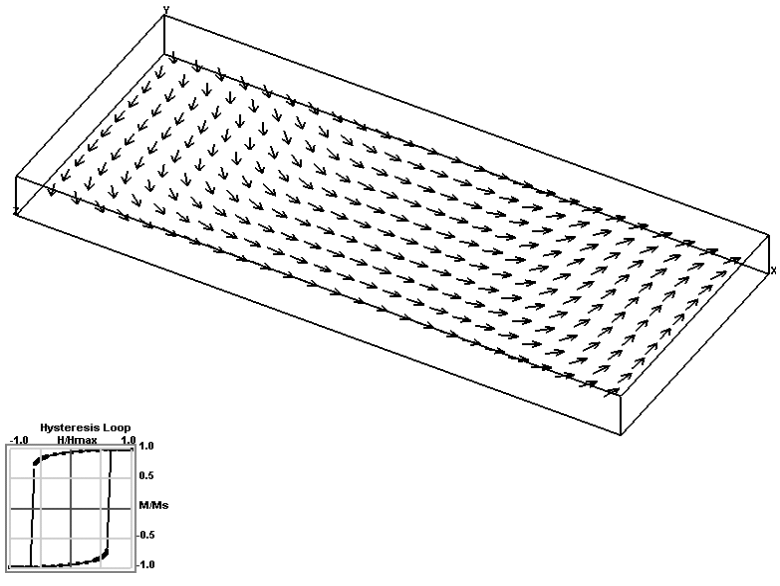
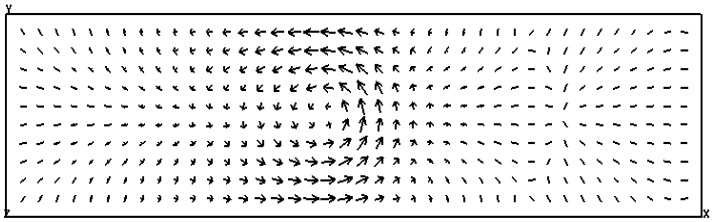


FIGURE 129. Surface Magnetization and Non-uniform Hysteresis Loop during Switching in 3D Arrows

CHAPTER 31

Sample Problem 6-Simulation for Asymmetric Bloch Wall in Permalloy



This is the simplest type of 2D problem. It simulates the structure of the so-called asymmetric Bloch wall, often termed the LaBonte wall. LLG has facilities to simulate the detailed structure of domain walls using the 2D Green's Function. A problem for a thin film of Permalloy is set up. The thickness of the film is selected to be thicker than that supporting a Néel wall, yet thinner than a film that supports bulk Bloch walls (and Néel surface caps).

INPUT SHEET - MAIN PAGE

Initiate an LLG computation. From the **Input Sheet-Main Page**, select the **2D** Green's Function, as is appropriate for the study of domain walls. Enter the dimensions of the problem: X(nm) is 400 nm and Y(nm) is 100 nm. Enter the discretization for the problem: N_X is 40 and N_y is 10.

INPUT SHEET - MATERIALS PAGE

1. Click the **Materials** tab.
2. Select **Permalloy**.
3. Click **Accept**. This loads the parameters for Permalloy into the edit fields in the Globals Page.
4. Click the **Globals** tab, then click **Accept Changes** on the **Globals Page** before you exit. This records Permalloy in the file name field in the Main Page.

INPUT SHEET - BOUNDARY CONDITIONS

1. Click the **Boundary** tab. The structure runs infinitely in the Z-direction. In a domain wall, the magnetization of the boundary conditions is fixed by the domains on either side of the wall.
2. Enter the domain orientations on either side of the wall into the **Boundary Conditions** fields. Enter **1.0** in the $\mathbf{M_z}$ edit field for the **Left X = 0** boundary condition and enter **-1.0** in the $\mathbf{M_z}$ edit field for the **Right X = N_x** boundary condition. These are the values of the direction cosines on the left and right sides of the structure. LLG will not change these values during the energy minimization process. The structure is now assumed to be infinite in the X-direction too, bounded on the left by Z-directed magnetization 1.0 and on the right by magnetization -1.0. The interior sub-elements adjacent to the boundaries will be exchange coupled to each boundary condition direction cosine. If the boundary conditions provide a component of the magnetization perpendicular to that boundary, at each interior point the magnetostatic field will be computed and stored due to the boundary magnetization.
3. Exit by clicking **Accept Changes**.

INPUT SHEET - COMPUTATION PAGE

1. Click the **Computation** tab.
2. Set the **Convergence** limit to 0.0001 and the **Iterations** to 2500.
3. Choose the **Energy (Slower)** method and the **Sequential** search method.
4. Click **Accept Changes** to exit.

INPUT SHEET - INITIALIZE PAGE

1. Click the **Initialize** tab.
2. Choose a **Narrow Wall** whose orientation is **X-Directed** as the initial condition by clicking the appropriate buttons in the **2D Narrow or Wide** and **2D Direction** fields, respectively.
3. Close the page by clicking **Accept Changes**.
4. Complete the initialization by clicking the **Begin Simulation** button.

COMMENTS

Notice that the sub-element size was specified to be 10 nm. This is near the upper limit that yields converged solutions for Permalloy. Rerun this sample with 80 and 20 sub-elements per side to see if any details were missed by selecting a coarse mesh. Rerun this sample again with a coarser mesh of 32 and 8 sub-elements per side to see if you can make the problem unstable. This sample problem is difficult to make unstable with the 1-Pt minimization method; however, if you coarsen the mesh, the solution eventually becomes unstable. The structure on the screen will be the asymmetric Bloch wall characterized by the tight vortex structure whose axis runs parallel to the surface of the film.

FEATURES

Structure:	400 nm x 100 nm
Sub-Element:	10 nm x 10 nm
Discretization:	40 x 10
Material:	Permalloy
Relaxation:	1-Pt Energy Minimization
Initialization:	Narrow Wall, X-Directed
Dimensions:	2
BC:	Left (M_z = 1.0) and Right (M_z = -1.0)

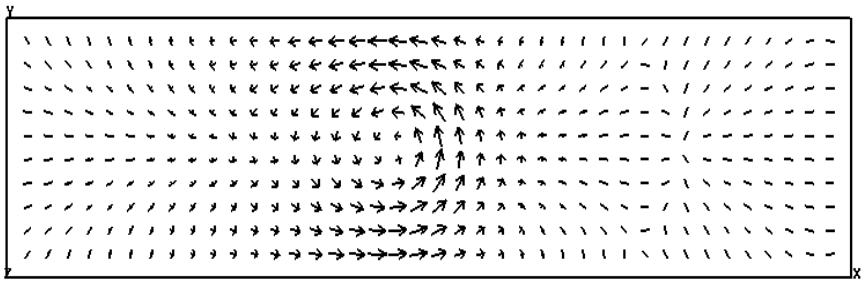


FIGURE 130. Magnetization Pattern in Cross Section in Arrows

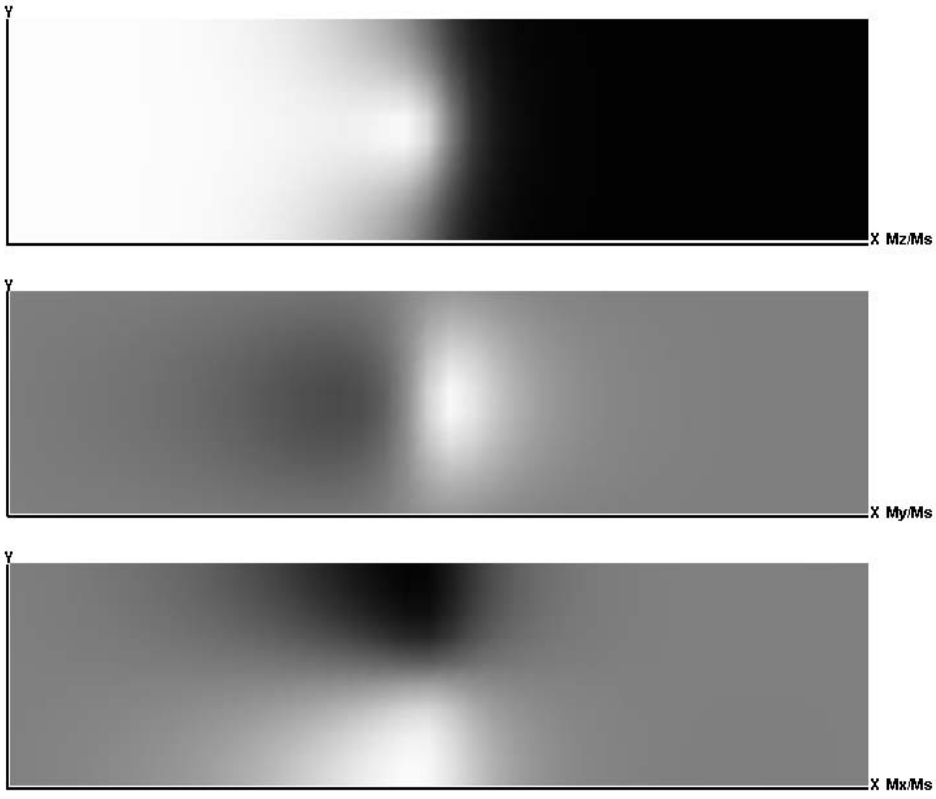


FIGURE 131. Magnetization Pattern in Cross Section in Bitmap

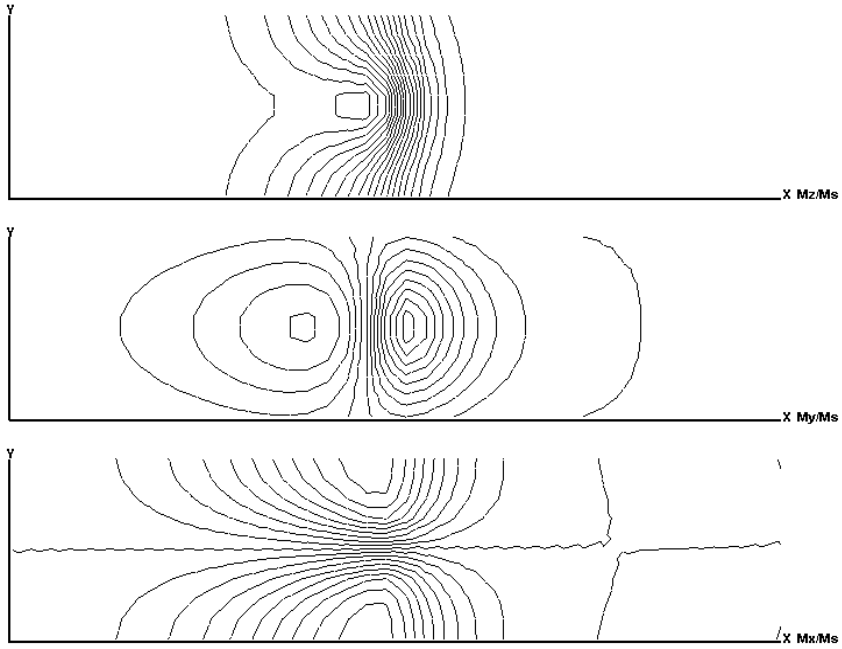


FIGURE 132. Magnetization Pattern in Cross Section in Contours

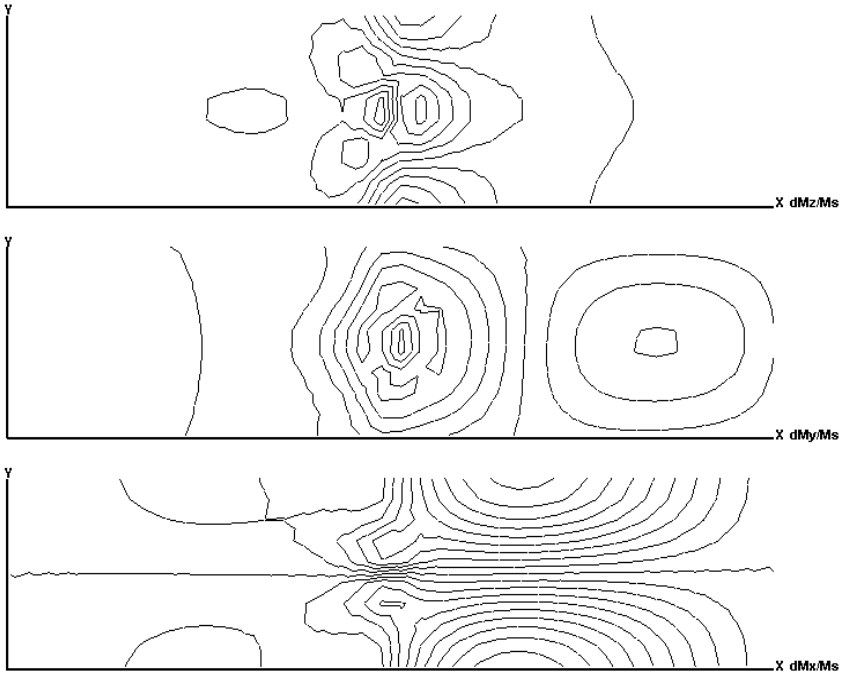
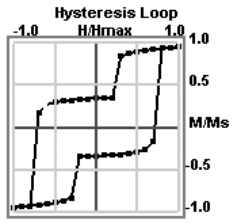


FIGURE 133. Residuals Pattern in Cross Section in Contours

CHAPTER 32

Sample Problem 7-Layers with Demag Coupling in MRAM



This is the first problem with multiple material layers. In the crudest sense, it is a two-layer MRAM system of a (relatively) hard layer, Fe, and a (relatively) soft layer, Permalloy. The two layers are antiferromagnetically coupled through their mutual demagnetization fields. There is no interlayer coupling; that is, they are exchange isolated by an ultra-thin layer of a non-magnetic and non-coupling material.

INPUT SHEET - MAIN PAGE

1. Initiate an LLG computation.
2. Enter the dimensions of the problem: X(nm) is 250 nm, Y(nm) is 100nm and Z(nm) is 20 nm.
3. Enter the discretization for the problem: N_x is 25, N_y is 10 and N_z is 2.
4. Check the **Layers** box to establish a multilayered problem.

INPUT SHEET - LAYERS PAGE

1. Click the **Layer Props** tab.
2. At the top right of the Layers Page use the arrow keys or the edit box to indicate **N Layers** of 2, that is, a two-layer problem. Then, you must specify the properties of each layer.
3. Set the **Layer #** to **1**, the first or lower layer.
4. Set the **Layer T(nm) Thickness** to **10** for layer 1.
5. Click the **Material** button at bottom center. Select **Permalloy** for the material and click **Accept** to return to the Layers Page. The properties for Permalloy should be loaded into the edit fields for the material properties of layer 1.
6. Use the color button at the bottom center to select green. The color should appear in the box on the button.
7. Click the **LOAD LAYER PROP** (red) button to register your entries for layer 1. You must click the **LOAD LAYER PROP** button after you enter each layer's properties.
8. Now, enter **2** in the edit field for **Layer #** to specify the properties of layer 2.
9. Set the **Layer T(nm) Thickness** to **10** for layer 2.
10. Click the **Material** button at bottom center and select **Fe** from the Materials Page.
11. Click **Accept** to return to the Layers Page; Fe properties have been entered into the edit fields.
12. Under Material Properties, set **A** (Exchange) for Fe to **2.1**.
13. Use the color button to select pink.

14. At the upper right, there is an edit field beneath A_{ij}. This is where you enter the exchange coupling parameter between the present layer, layer 2, and the adjacent layers, layer 1 or 3. Since there is no boundary layer, layer 3 coupling is irrelevant. However, the interlayer coupling between layers 1 and 2 should be zero. Therefore, enter **0.0** into the edit field adjacent to **Aij 1**. This turns off the coupling between layers 1 and 2. Note that you can enter any coupling parameter, including antiferromagnetic coupling (Aij < 0.0).
15. Click the **LOAD LAYER PROP** (red) button to register your entries for layer 2. You must click the **LOAD LAYER PROP** button after you have entered each layer's properties.

    IMPORTANT NOTE: *You must insure that*:

    The total thickness of the layers equals the total thickness of the structure. The thickness of each layer is an integral multiple of the sub-element width in the Z-direction. In this problem, layers 1 and 2 are each 10 nm, for a total thickness of 20 nm. There are two layers specified in Z in 20 nm, which makes the integral layer thickness compliant at 10 nm.

    When you try to exit the page by clicking Accept Changes, LLG checks for compliance and warns you if the parameters are set incorrectly. LLG places layer 1 on the bottom (Z = 0) of the structure and places layer 2 above layer 1 at an increased value of the coordinate Z. The interlayer coupling between layers 1 and 2 should be set to zero. This completes the layer parameter initialization.
16. Click **Accept Changes** to exit and record your entries.

INPUT SHEET - COMPUTATION PAGE

1. Click the **Computation** tab.
2. Set the **Convergence** limit to **0.0001** and the **Iterations** to **25000**. There are no boundary conditions or externally applied currents in this problem.
3. Use the **3D Complex FFT method** to compute the solution to the LLG equations.
4. Set the **Time Step** to **4.0 ps**. This entry will be revisited once the simulation has been initialized.
5. Click **Accept Changes** to exit and record your entries.

INPUT SHEET - INITIALIZE PAGE

1. Click the **Initialize** tab.
2. Click the **Uniform X-Direction** button in the **3D Uniform Magnetization** field.
3. Notice that the **Sign On Uniform** options default to Positive, with Theta 90.0 (magnetization in the X-Z plane) and Phi 0.0 (magnetization along the X-axis). Enter **30.0** into the **Phi** edit field to cant the initial magnetization off the X-axis by 30^o.
4. Click **Accept Changes** to exit and record your entries.

INPUT SHEET - UNIFORM HYSTERESIS PAGE

This problem has no static external fields and none of the layers is exchange pinned. To complete the problem set-up, you need to specify only the hysteresis loop options.

1. Click the **Hys-U** tab.
2. Select the **Uniform** mode. Set **H_x(Oe)** to **1250.0 Oe**.
3. Set the # **Points** (on one branch) to **21**.
4. Click **Accept Changes** to exit and record your entries.
5. Problem specification is complete. Save your input file. Run the problem and save a movie file.

SIMULATION SHEET

Once the Simulation Sheet appears:

1. Divide the screen in half and place the hysteresis loop in the upper pane.
2. Divide the lower pane in half. Click on the lower right pane.
3. Click the **Modes** tab, and then click the color button (**CO**) next to **3D Slice**.
4. Click the **Orient** tab, then move the layer selection with the **View** slide bar.

You can visualize changes in layers 1 and 2 simultaneously. Notice the complex hysteresis loop that results from the coupling between the layers.

FEATURES

Structure:	250 nm x 100 nm x 20 nm
Sub-Element:	10 nm x 10 nm x 10 nm
Discretization:	25 x 10 x 2
Material:	Permalloy (layer 1) and Fe (layer 2)
Relaxation:	3D Complex FFTs
Initialization:	Uniform magnetization, directed 30^o off the long axis
Hysteresis:	Uniform, H_x = 1250 Oe, N_{pts} = 21
Coupling:	Interface exchange coupling = 0

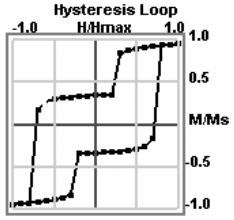
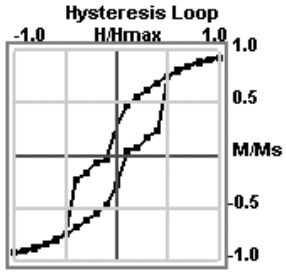


FIGURE 134. Hysteresis Loop Showing Antiferromagnetic Coupling between the Layers

CHAPTER 33

Sample Problem 8- Antiferromagnetic Exchange Coupled Permalloy Platelets



This is the second sample problem with multiple material layers. It has two layers of Permalloy, which are antiferromagnetically coupled through exchange at the interface. In all other ways, this problem is identical to Sample 7.

INPUT SHEET - MAIN PAGE

1. Initiate an LLG computation.
2. Enter the dimensions of the problem: X(nm) is 250 nm, Y(nm) is 100 nm and Z(nm) is 20 nm.
3. Enter the discretization for the problem: N_x is 25, N_y is 10 and N_z is 2.
4. Select **Layers** in the **Structure Properties** group box.

INPUT SHEET - LAYER PROPERTIES PAGE

1. Click the **Layer Props** tab.
2. Enter **2** in the **N Layers** edit field.
3. Enter **1** in the **Layer #** edit field. Set the **Layer Thickness** to **10.0**. Click the **Material** button. Select **Permalloy** and click **Accept**. Click **LOAD LAYER PROP** to define the material for layer 1.
4. Enter **2** in the **Layer #** edit field. Set the **Layer Thickness** to **10.0**. Click the **Material** button. Select **Permalloy** and click **Accept**. Click **LOAD LAYER PROP** to define the material for layer 2.
5. Compute the interlayer coupling for 10 nm thick films of permalloy as $H_{exchange}$ = -400Oe =>$A_{interlayer(1->2)}$= -0.16erg/cm. Scroll back to layer 1. Enter **A10 = 0.0** and **A12 = -0.16**. Click **LOAD LAYER PROP** to register your changes.
6. Exit the page by clicking **Accept Changes**.

INPUT SHEET - COMPUTATION PAGE

These are identical to Problem 7.

INPUT SHEET - INITIALIZE PAGE

These are identical to Problem 7.

INPUT SHEET - HYSTERESIS-UNIFORM PAGE

These are identical to Problem 7.

COMMENTS

Notice that the magnetization layers are the same and that the total magnetization is nearly zero at zero field in the antiferromagnetic state.

FEATURES

Structure: 250 nm x 100 nm x 20 nm

Sub-Element: 10 nm x 10 nm x 10 nm

Discretization: 25 x 10 x 2

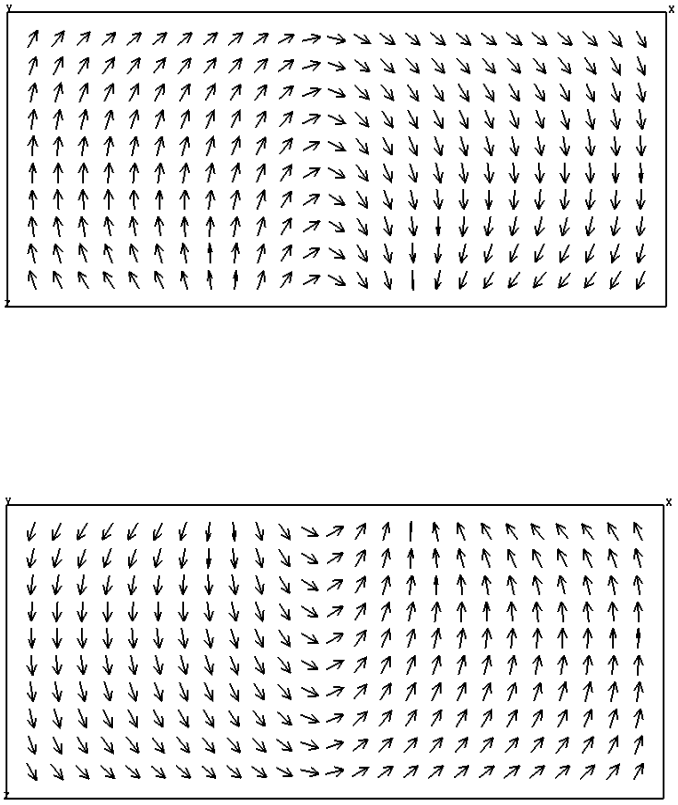
Material: Permalloy (layer 1) and Permalloy (layer 2)

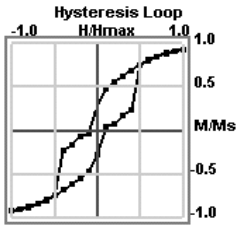
Relaxation: 3D Complex FFTs

Initialization: Uniform magnetization, directed 30^o off the long axis

Hysteresis: Uniform, H_x = 1250 Oe, N_{pts} = 21

Coupling: Antiferromagnetic exchange coupling, strength -400.0 Oe

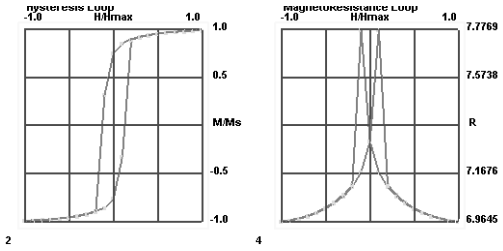




Magnetization Pattern in Layer 1 Near Zero Field in Arrows (top) and Magnetization Pattern in Layer 2 Near Field in Arrows (bottom)

CHAPTER 34

Sample Problem 9-GMR for Bilinear Interlayer Exchange between Platelets



This is the third sample problem with multiple material layers. It has two layers of Permalloy that are separated by a non-magnetic Cu layer. The two layers are antiferromagnetically coupled through a GMR-type exchange at the interfaces of the two magnetically active layers across the Cu interlayer. In addition, current is flowing along the X-axis and a GMR ratio of 0.25 has been attributed to the magnetoconductance of the active layers. Fields from the driving currents are included in the simulation. Both the hysteresis and MR loops can be visualized during the computation.

INPUT SHEET - MAIN PAGE

1. Initiate an LLG computation.
2. Enter the dimensions of the problem: X(nm) is 250 nm, Y(nm) is 100 nm and Z(nm) is 30 nm.
3. Enter the discretization for the problem: N_x is 25, N_y is 1 and N_z is 3.
4. Select **Layers** in the **Structure Properties** group box.

INPUT SHEET - COMPUTATION PAGE

These are identical to Problems 7 and 8.

INPUT SHEET - LAYER PROPERTIES PAGE

1. Click the **Layer Props** tab.
2. Enter **3** in the **N Layers** edit field.
3. Enter **1** in the **Layer #** edit field.
4. Set the thickness of layer 1 to **10.0** in the **Thickness T(nm)** edit field.
5. Click the **Material** button.
6. Select **Permalloy** and click **Accept**.
7. Set the interlayer exchange coefficients $\mathbf{A_{10}}$ and $\mathbf{A_{12}}$ equal to **0**.
8. Click the **LOAD LAYER PROP** button to record your changes.
9. Enter **2** in the **Layer #** edit field.
10. Set the thickness of layer 2 to **10.0** in the **Thickness T(nm)** edit field.
11. Click the **Material** button.
12. Select **Vacuum** and click **Accept**.

13. Set the resistivity (**Rho**) to **5.0** μOhm-cm to approximate Cu.
14. Set the interlayer exchange coefficients $\mathbf{A_{21}}$ and $\mathbf{A_{23}}$ equal to 0. Set the **Bilinear** exchange coupling coefficient to -0.16 μerg/cm (-400Oe, see Problem 7).
15. Set the **GMR** value to **0.25**.
16. Press the **LOAD LAYER PROP** button to record your changes.
17. Enter **3** in the **Layer #** edit field.
18. Set the thickness of layer 3 to **10.0** in the **Thickness T(nm)** edit field.
19. Click the **Material** button.
20. Select **Permalloy** and click **Accept**.
21. Set the interlayer exchange coefficients $\mathbf{A_{32}}$ and $\mathbf{A_{34}}$ equal to **0**.
22. Click the **LOAD LAYER PROP** button to record your changes.
23. Click **Accept Changes** to record the variables.

INPUT SHEET - CURRENT PAGE

1. Click the **Current** tab.
2. Select **2D** for the current.
3. Set the direction to be **X**.
4. Enter **1000.0** in the **Current (μA)** edit field.
5. Click **Accept Changes** to record the variables.

INPUT SHEET - INITIALIZE PAGE

These are identical to Problems 7 and 8.

INPUT SHEET - HYSTERESIS-U PAGE

These are identical to Problems 7 and 8.

Problem specification is complete. Click the **Begin Simulation** button.

SIMULATION SHEET - SIMULATION PAGE

Once the **Simulation Sheet-Simulation Page** is visible, divide the screen into four quadrants. Put the hysteresis loop in the upper left, the MR loop in the upper right, the lower layer magnetization is the lower left and the upper layer magnetization in the lower right. Run the problem and save a movie file. Notice the complex hysteresis and MR loops that result from the coupling between the layers.

COMMENTS

Notice that the magnetization layers are the same and that the total magnetization is zero in the antiferromagnetic state.

FEATURES

Structure:	250 nm x 100 nm x 30 nm
Sub-Element:	10 nm x 10 nm x 10 nm
Discretization:	25 x 10 x 3
Material:	Permalloy (layer 1), Non-magnetic Cu (layer 2) and Permalloy (layer 3)
Relaxation:	3D Complex FFTs
Initialization:	Uniform magnetization, directed 30^o off the long axis
Hysteresis:	Uniform, H_x = 1250 Oe, N_{pts} = 21
Coupling:	Antiferromagnetic coupling across a non-magnetic layer, strength -400.0 Oe (-0.16 μerg/cm)

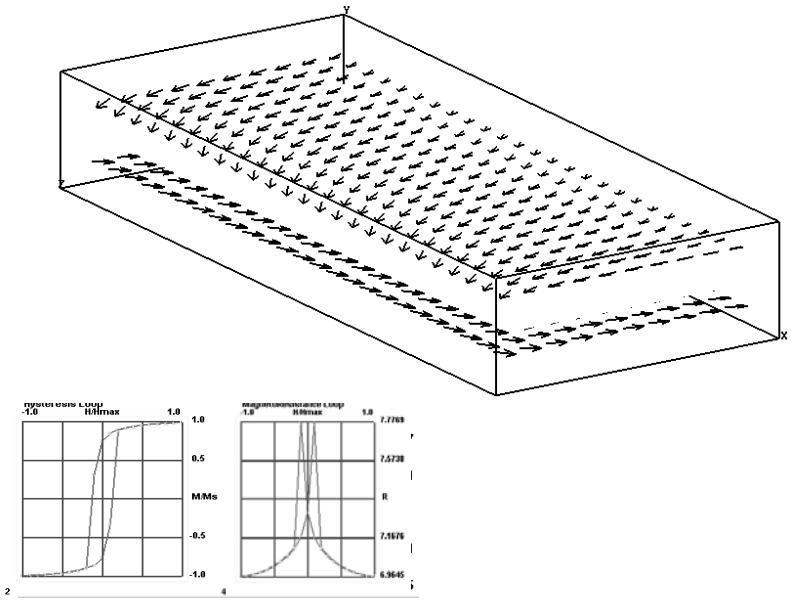
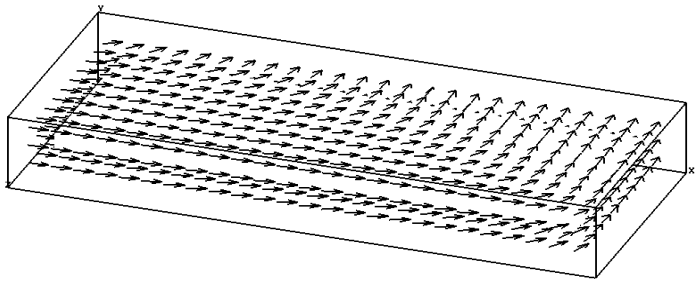


FIGURE 135. Magnetization Near Zero Field in 3D Arrows

CHAPTER 35

Sample Problem 10-Boundary Conditions Applied to a Thin Platelet



This sample illustrates using boundary conditions for a three-dimensional problem, including creating and storing position-dependent field files. It is a thin Permalloy platelet with permanent magnets on two sides.

INPUT SHEET - MAIN PAGE

1. Initiate an LLG computation.
2. Enter the dimensions of the problem: X(nm) is 250 nm, Y(nm) is 100 nm and Z(nm) is 30 nm.
3. Enter the discretization for the problem: N_x is 25, N_y is 10 and N_z is 3.
4. Select **Layers** in the **Structure Properties** group box.

INPUT SHEET - COMPUTATION PAGE

1. Click the **Computation** tab.
2. Set the **Convergence** limit to **0.0001** and the **Iterations** to **2500**.
3. Choose **Time (Faster)** and **2D Real FFT Method**.
4. Click **Accept Changes** to log your changes.

INPUT SHEET - GLOBALS PAGE AND MATERIALS PAGE

1. Click the **Globals** tab.
2. Click the **Material** button.
3. Select **Permalloy** and click **Accept**. The Permalloy properties should be entered in the edit fields of the Globals Page.
4. Click **Accept Changes** to log your changes.

INPUT SHEET - BOUNDARY CONDITIONS PAGE

1. Click the **Boundary** tab.
2. Enter the permanent magnet orientations on two of the six sides into the Boundary Conditions edit fields. Enter **1.0** in the **Mx** edit field for the **Left X = 0** boundary condition and **-1.0** in the **My** edit field for the **Back Y = Ny** boundary condition. These are the values of the direction cosines on the left and back sides of the structure. They represent permanent (Permalloy) magnets, the first magnetized positively along X and positioned just to the left of the structure, and the second magnetized negatively along Z and positioned at the back of the structure. LLG will not change these values in the energy minimization process. Due to the boundary magnetization adjacent to the boundaries,

the interior sub-elements will be exchange coupled to each boundary condition direction cosine and, due to the normal component of boundary magnetization, the magnetostatic field at each interior point will be computed and stored.

3. Check the **Write File** box.
4. Click the **Output File Name** button and enter a name for the boundary condition H-field file. This instructs LLG to store the values of the field at each point in the structure to a file after the values have been computed. Note, you are also afforded the opportunity to save field files in the Simulation Sheet-View Page once a simulation has been initiated.
5. Exit the page by clicking **Accept Changes** to log your changes.

IMPORTANT NOTE:

Saving the boundary condition field is important. This is related to LLG's method for solving boundary value problems. In LLG, the direction cosines are fixed on the boundaries in sheets of sub-elements. If the moments have a component of their magnetization perpendicular to the boundary, the charge at the boundary produces a field within the structure. As such, LLG modifies a problem in two ways when you use boundary conditions.

- First, the sheet of sub-elements adjacent to the boundary will exchange couple to the boundary sub-element direction cosines.
- Second, the effect of any stray field from the boundaries is included at every point in the structure of consideration. Internal to LLG, these effects are independent.

This means that you can provide a means of having NON-EXCHANGE COUPLED boundary conditions in the following way. For example, you might want to simulate a structure that has permanent magnets made of CoPt at either end of the structure; yet, you do not want the magnets exchange coupled to the simulation volume.

Begin a new simulation with a structure the same size and shape as your system under study. Select the properties of your permanent magnet material for the global parameters; for example, the properties of CoPt, if you know them. Click the **Boundary** tab and input the permanent magnet orientations. Click the **Save H-Field File** button to save the file. Complete the LLG initialization. The status bar indicates that first the tensors and then the boundary condition fields are being computed. Then, LLG writes the fields to a file. Exit when the Simulation Sheet appears. Start a new problem, this time loading your real structure's parameters into the Input Sheet fields. Open the Boundary Conditions Page and click the **Read H-Field File** button. Enter the filename with the permanent magnet field files. Load the file, them complete problem specification. You will find that the stray field from the permanent magnets is included in the external fields to which your structure is subjected.

INPUT SHEET-INITIALIZE PAGE

Back to the problem of interest.

1. Click the **Initialize** tab.
2. Click the **Uniform X-Direction** button in the **3D Uniform Magnetization** field.
3. Notice that the **Sign On Uniform** options default to Positive, with Theta 90.0 (magnetization in the X-Z plane) and Phi 0.0 (magnetization along X-axis). Enter **10.0** into the **Phi** edit field to cant the initial magnetization off the X-axis by 10^0.
4. Close this page by clicking **Accept Changes**.
5. Click the **Begin Simulation** button. Run the problem.

COMMENTS

Notice how the magnetization follows the flux lines from the stray field of the external magnets, as expected. This is due in part to the stray field and in part to exchange. This feature adds flexibility to the structures that you can simulate with LLG. The use of boundary conditions also allows you to simulate smaller volumes (regions of interest) within larger structures.

FEATURES

Structure: 250 nm x 100 nm x 30 nm

Sub-Element: 10 nm x 10 nm x 10 nm

Discretization: 25 x 10 x 3

Material: Permalloy

Relaxation: 2D Real FFTs and Rotation Matrices

Initialization: Uniform magnetization, directed 10^{o} off the long axis

Boundary Cond: Permanent exchange coupled magnets on two faces

NOTE: In the graphic below, the structure has been rotated for a view from the back. The magnetization pattern is the top picture.

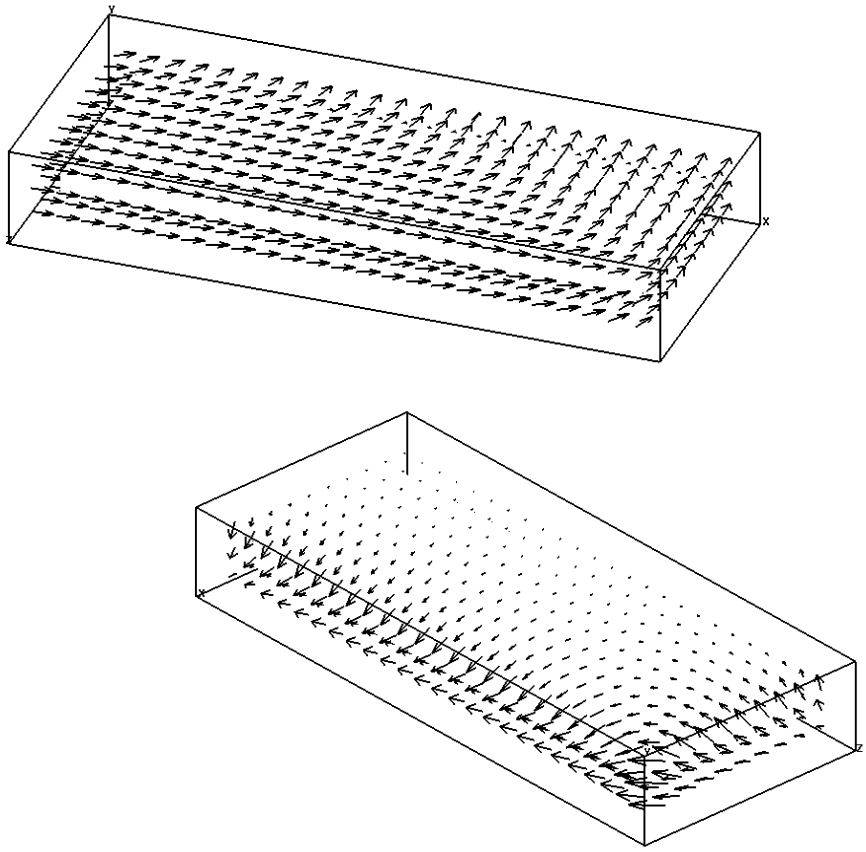
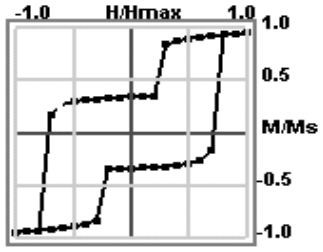
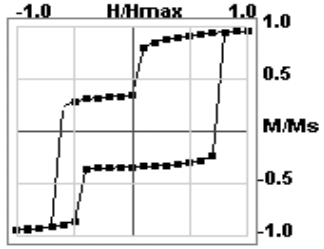


FIGURE 136. Magnetization Pattern and Boundary Conditions Fields in 3D Arrows

CHAPTER 36

Sample Problem 11-Non-uniform Hysteresis Loop for a Pinned Platelet





This sample illustrates the use of pinning fields in solving micromagnetics problems. Pinning fields can be the result of many different physical phenomena. For example, LLG uses them to capture the effects of antiferromagnetic pinning at an interface (spin-valves) by applying a fixed bias field to a given sub-element layer. This saves computation time because the pinning-layer antiferromagnet need not be included in the simulation volume. Alternatively, the pinning field can be used to make films locally harder (for whatever physical mechanism you are trying to model). As far as LLG is concerned, the pinning fields are just another external, position-dependent field that is added to the list of fields to which the magnetic moments are subjected.

INPUT SHEET - EXTERNAL/PINNING FIELDS

1. Initiate an LLG computation. Initialize the problem as in Sample Problem 7.
2. Click the **Fields** tab.
3. Use the slide bar or edit box to enter a **250.0 Oe** pinning field in the **Hx(Oe) Pinning Field** input area.
4. Click the **Load H-Pin** button to load the field. Make sure that 1 appears in the **Layer to Pin** field, so that this field is applied only to the bottom (Fe) layer.
5. Click **Accept Changes** and exit the page.
6. Click **Begin Simulation** and run the problem.

COMMENTS

Compare these results with those from Problem 7. Observe the shift in the hysteresis loop.

FEATURES

Structure: 250 nm x 100 nm x 20 nm

Sub-Element: 10 nm x 10 nm x 10 nm

Discretization: 25 x 10 x 2

Material: Permalloy (layer 1) and Fe (layer 2)

Relaxation: 3D Complex FFTs

Initialization: Uniform magnetization, directed 30^o off the long axis

Hysteresis: Uniform, H_x = 1250 Oe, N_{pts} = 21

Coupling: Interface exchange coupling = 0

Pinning Fields: H_x = 250 Oe on sub-element layer Z = 1 (Permalloy)

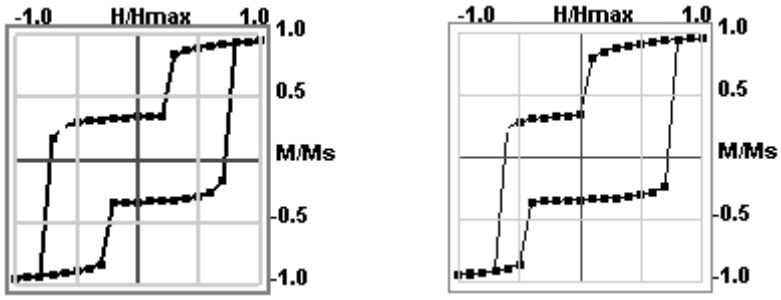
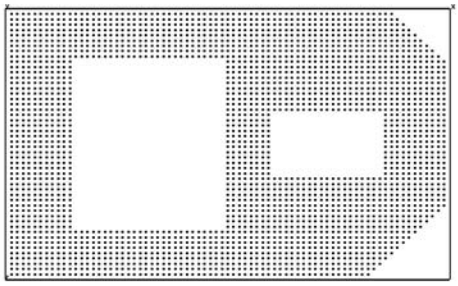


FIGURE 137. Hysteresis Loop from Unpinned Problem and 250 Oe Field Pinning

CHAPTER 37

Sample Problem 12-Shaping Magnetic Elements



This problem illustrates the use of the Mask Editor for shaping the magnetic simulation volume. Holes can be cut into a structure arbitrarily in three dimensions. Corners can be cut off and roughness can be added along edges or at interfaces. The Mask Editor was designed for flexibility in creating realistic and non-Cartesian structures. With the Mask Editor you can remove cells (sets the magnetization on or off).

IMPORTANT NOTE: Any curved surface constructed with LLG is digital, i.e., jagged. To date, the presence of jagged edges has not had any deleterious effects on the outcome of the problem, as long as the sub-element size is appropriately small so that the magnetic stray field can easily couple across the vacuum interface. In a real structure with curved boundaries, there would be some magnetic material.

INPUT SHEET - MAIN PAGE

1. Enter the dimensions of the problem: X(nm) is 750 nm, Y(nm) is 500 nm and Z(nm) is 10 nm.
2. Enter the discretization for the problem: N_x is 75, N_y is 50 and N_z is 1

INPUT SHEET - COMPUTATION PAGE

1. Set the **Convergence** limit to **0.0001** and the **Iterations** to **2500**.
2. Set the **Time Step** to **2.0 ps**.
3. Click **Accept Changes**.

INPUT SHEET - MATERIALS PAGE

1. Select **Permalloy** in the **Materials Page**.
2. Click **Accept**; the Permalloy properties should be entered in the edit fields of the Globals Page.
3. Click **Accept Changes** to log your changes.

INPUT SHEET - MASK AND VIEW PAGE

1. Check the **Commit Size** box on the **Main Page**. This commits the memory, fixes the sample size and allows you to use the **Mask Editor**.
2. Click the **Masks** button on the **Main Page**. The **Mask Editor** and **View Page** appear. Your initial view of the structure will be from the top. All of the sub-elements will be painted yellow, indicating that the magnetization is active within each cell.
3. Use the drawing tool to form the element into the same shape as the one above and on the following page. Active cells appear yellow and removed cells appear blue. Save your mask once you have completed forming the structure. You can import a given mask into a new problem, which LLG will interpolate if the meshes are different.

4. Click **Accept Changes** and return to the Main Page.
5. Click **Begin Simulation** and run the problem.

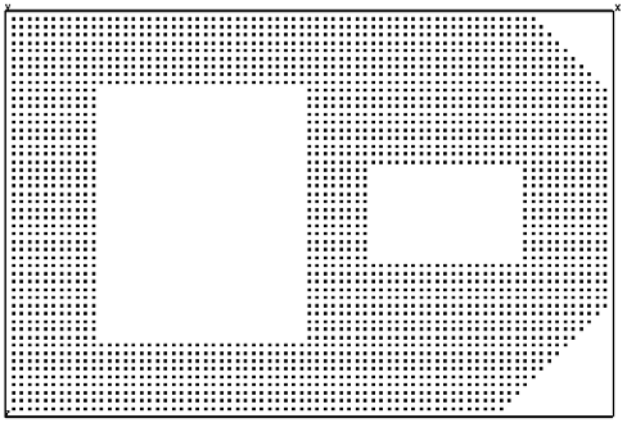


FIGURE 138. View of Mask

COMMENTS

Observe how the magnetization runs parallel (nearly parallel) to the edges defined by the mask, which is consistent with minimizing the stray field energy.

FEATURES

Structure: 750 nm x 500 nm x 10 nm

Sub-Element: 10 nm x 10 nm x 10 nm

Discretization: 75 x 50 x 1

Material: Permalloy

Relaxation: FFTs

Initialization: Vortex in Y

Mask Editor: Shaped structure

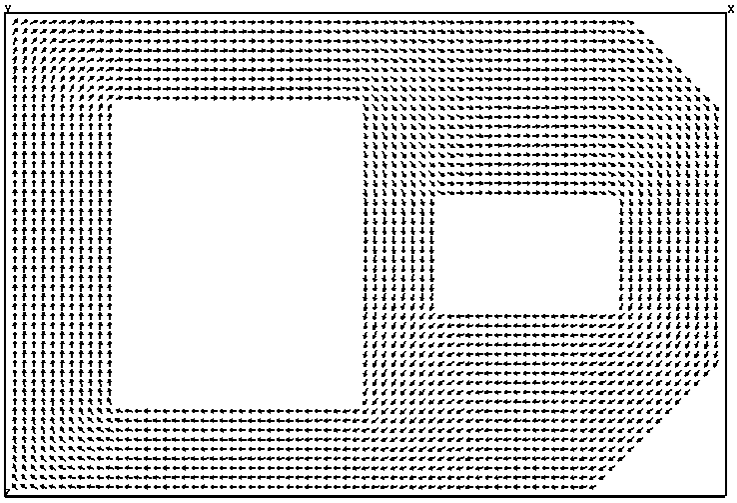
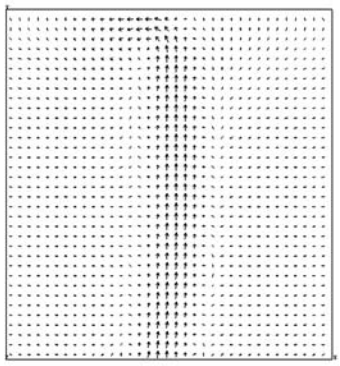


FIGURE 139. Magnetization Pattern in Arrows Graph Type

CHAPTER 38

Sample Problem 13-Bulk Terminated Bloch Wall in Fe



This sample problem illustrates the formation of Bloch and Néel walls at or near a surface region local to a domain wall in 2D structures. The sample solves the micromagnetic structure for a Fe domain wall, including the bulk Bloch wall and the Néel cap.

INPUT SHEET - MAIN PAGE

1. Initiate an LLG computation.
2. From the **Main Page**, click the **2D** button to use the **2D Green's Function**, as is appropriate for the study of domain walls.
3. Enter the dimensions of the problem: X(nm) is 500 nm and Y(nm) is 500 nm.
4. Enter the discretization for the problem: N_x is 70 and N_y is 70.

INPUT SHEET - COMPUTATION PAGE

1. Click the **Computation** tab.
2. Set the **Convergence** limit to **0.0001** and the **Iterations** to **25000**.
3. Choose **Energy (Slower)** and a **Sequential** search.
4. Exit by clicking **Accept Changes**.

INPUT SHEET - GLOBALS PAGE AND MATERIALS PAGE

1. Click the **Globals** tab and click the **Material Selecto**r button.
2. Select **Fe** from the **Materials Page**.
3. Click **Accept**; the Fe properties should be entered in the edit fields of the Globals Page.
4. Exit the page by clicking **Accept Changes**.

INPUT SHEET - BOUNDARY CONDITIONS PAGE

1. Click the **Boundary** tab.
2. The structure runs infinitely in the Z-direction. In a domain wall, the domains on either side of the wall fix the magnetization. Enter the domain orientations on either side of the wall into the **Boundary Conditions** edit fields. Enter **1.0** in the **M_z** edit field for **Left X=0** and **-1.0** in the **M_z** edit field for the **Right X=N_x** boundary conditions.
3. Exit by clicking **Accept Changes**.

INPUT SHEET - INITIALIZE PAGE

1. Click the **Initialize** tab.
2. Click **2D Narrow Wall** as the initial condition and **2D X-Directed** fields.
3. Exit the page by clicking **Accept Changes**.
4. Complete the initialization by clicking the **Begin Simulation** button. Run the problem.

COMMENTS

Notice that the sub-element size was specified to be about 7 nm. This is near the upper limit that yields converged solutions for Fe. Also, note that the Simulation Volume was set large in case the resulting micromagnetic structure was constrained due to the boundaries.

FEATURES

Structure: 500 nm x 500 nm

Sub-Element: 7.14 nm x 7.14 nm

Discretization: 70 x 70

Material: Fe

Relaxation: 1-Pt Energy Minimization

Initialization: Narrow Wall

Dimensions: 2

Boundary Cond: Left (M_z = 1.0) and Right (M_z = -1.0)

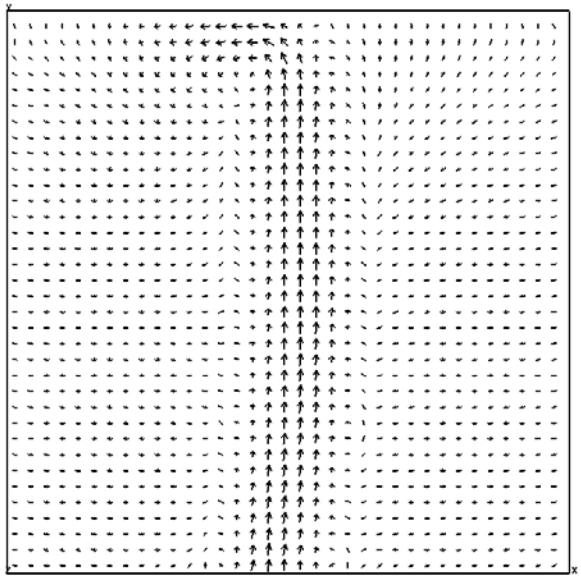


FIGURE 140. Magnetization Pattern in Cross Section Near the Top of the Bulk Terminated Bloch Wall

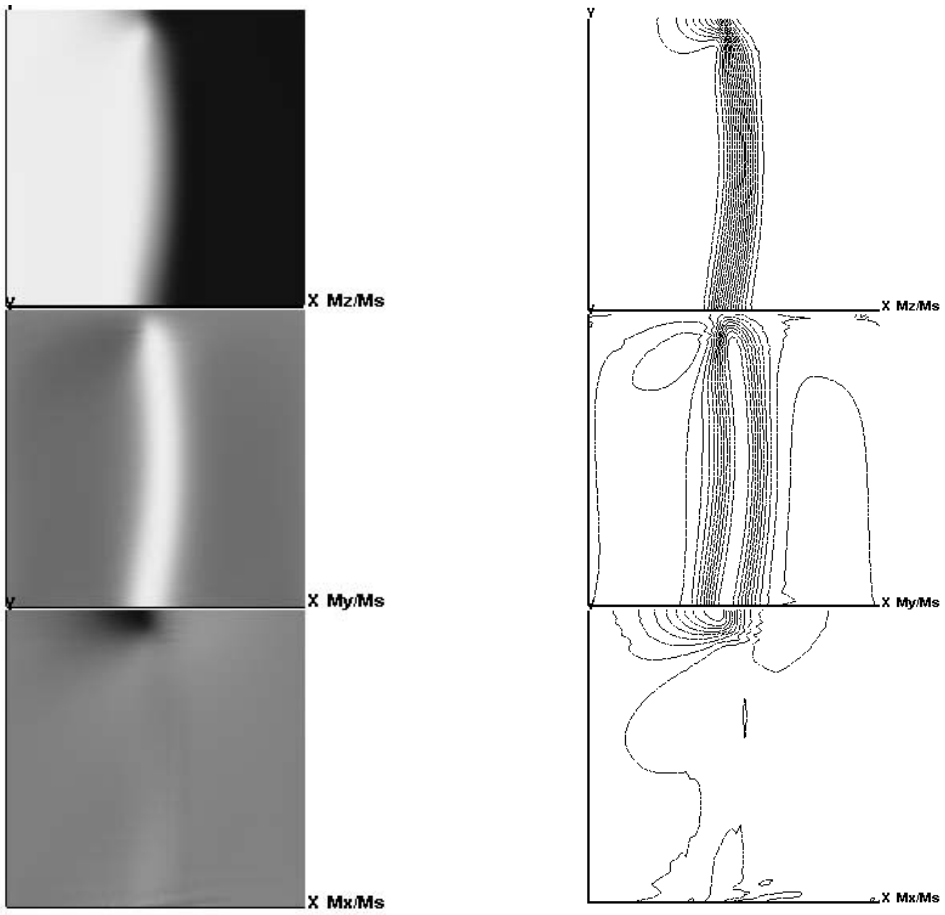
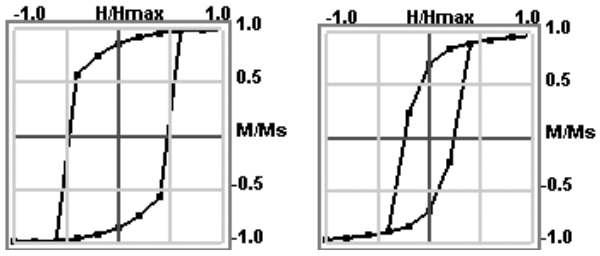


FIGURE 141. Magnetization Pattern in Bitmap and Contour Near the Top of the Bulk Terminated Bloch Wall

CHAPTER 39

Sample Problem 14-Easy/Hard Axis Hysteresis Loops in a Platelet



This sample problem illustrates the use of the Any direction anisotropy on the switching properties of a thin platelet of hard ($K_u = 10^5$ erg/cm3) Permalloy.

INPUT SHEET - MAIN PAGE

1. Initiate an LLG computation.
2. Enter the dimensions of the problem: X(nm) is 150 nm, Y(nm) is 150 nm and Z(nm) is 10 nm.
3. Enter the discretization for the problem: N_x is 15, N_y is 15 and N_z is 1.

INPUT SHEET - COMPUTATION PAGE

1. Click the **Computation** tab.
2. Set the **Convergence** limit to **0.001** and the **Iterations** to **250**.

INPUT SHEET - GLOBALS PAGE AND MATERIALS PAGE

1. Click the **Global** tab. Then, click the **Material Selector** button.
2. Select **Permalloy** from the **Materials Page**.
3. Click **Accept**; the Permalloy properties should be entered in the edit fields of the Globals Page.
4. Click the **Any** button under **Easy Axis**.
5. Enter **1.0** in the **Ax** and **Ay** edit fields of the **UNIAXIAL** section. You can enter numbers between -1.0 and 1.0. LLG will normalize them to a unit vector.
6. Click **Accept Changes** to log your changes.

INPUT SHEET - INITIALIZE PAGE

1. Click the **Initialize** tab.
2. Initialize the magnetization **10^o** (**Phi**) from X in the X-Y plane.
3. Click **Accept Changes** to log your changes.

INPUT SHEET - HYSTERESIS PAGE

1. Click the **Hysteresis** tab.
2. Select the **Uniform** mode. Set **Hx (Oe)** to **1000.0.**
3. Set the **# Points** (on one branch) to **11**.
4. Click **Accept Changes** to log your changes. Run the problem.

RERUN THE PROBLEM

Re-initiate an LLG computation. Load the previously saved file. This time force the easy axis to be along X. Exit the page. Begin the calculation and save a movie.

COMMENTS

The difference in the remanence and coercivities is evidence for the different orientation of the easy axis. The sample with the easy axis oriented at 45^o from X in the X-Y plane has a coercivity of about 200 Oe and a zero-field magnetization of about $0.61M_S$ (saturated). The sample with the easy axis aligned along the X-plane has a coercivity of about 450 Oe and a zero-field magnetization of about $0.86M_S$ (saturated). Use the Any direction option to orient the direction of the easy axis in your films.

FEATURES

Structure:	150 nm x 150 nm x 10 nm
Sub-Element:	10 nm x 10 nm x 10 nm
Discretization:	15 x 15 x 1
Material:	Permalloy
Relaxation:	1-Pt Energy Minimization
Initialization:	10^o from X in the X-Y plane
Hysteresis:	Uniform, H_x = 1000 Oe, N_{pts} = 11
Anisotropy:	Any at 45^o from X in the X-Y plane

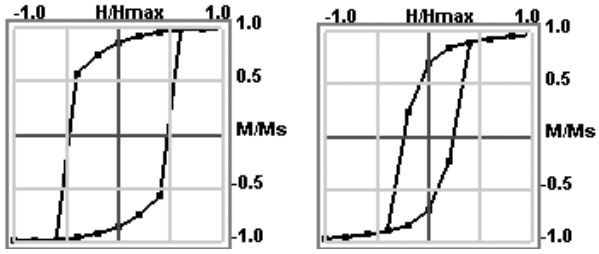
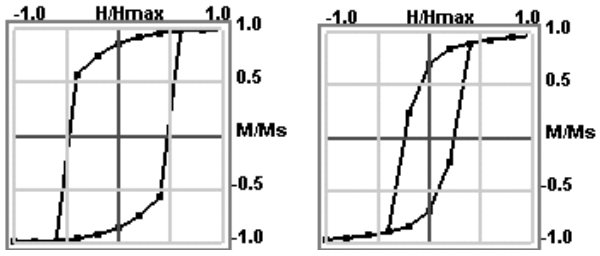


FIGURE 142. Hysteresis Loops Taken along the Easy Axis and at 45^o from the Easy Axis

CHAPTER 40

Sample Problem 15- Magnetization Dynamics in Permalloy Platelets



This sample problem illustrates the use of time integration to keep track of temporal changes in the magnetization over time.

INPUT SHEET - MAIN PAGE

1. Initiate an LLG computation.
2. Enter the dimensions of the problem: X(nm) is 150 nm, Y(nm) is 150 nm and Z(nm) is 10 nm.
3. Enter the discretization for the problem: N_x is 15, N_y is 15 and N_z is 1.
4. Check the **Save Conv Details** box and enter **10** in the **Every N Iterations** edit box. This will save the energies and remanence every 20 ps.

INPUT SHEET - COMPUTATION PAGE

1. Click the **Computation** tab.
2. Deselect the **Convergence** and **Iterations** boxes.
3. Check the **Stop t(ns)** box and enter **2.0 ns** for the **Stop t(ns)**.
4. Enter **0.02** for **Alpha.**
5. Check **Time (Faster).**
6. Select the **2D Real FFT** method and set the **(ps) Time Step** to **1.0**.
7. Click the **Predictor-Corrector Time Integration** method. This method should be used for all problems where alpha is <0.5.
8. Click **Accept Changes** to log your changes.

INPUT SHEET - GLOBALS PAGE AND MATERIALS PAGE

1. Click the **Globals** tab and click the **Material Selector** button.
2. Select **Permalloy** from the **Materials Page**.
3. Click **Accept**. The Permalloy properties should be entered in the edit fields of the Globals Page.
4. Click **Accept Changes** to log your changes.

INPUT SHEET - INITIALIZE PAGE

1. Click the **Initialize** tab.
2. Initialize the magnetization along **Negative** X in the X-Y plane.
3. Click **Accept Changes** to log your changes.

INPUT SHEET - TIME DEP-H PAGE

1. Click the **Time-Dep H** tab.
2. Check the **Time Dep Field** box to activate the time-dependent fields.
3. Enter **100** into the **Time Interval (steps)** edit box. Leave the **Time Step (ps)** at **1ps**. This will be the rise time for the field, that is, 100 x 1ps = 100ps.
4. Enter **0.0 Oe** and **500.0 Oe** into the **H_x T-1(ps)** and **H_x T-2(ps)** edit boxes, respectively. These are the fields at t = 0 and t = 100 ps, respectively.
5. Click the **LOAD SECTION** button to log that section into the data structure.
6. Increment the **Time Interval Specified** to **2**.
7. Enter **1900** into the **Time Interval (ps)** edit box. This will be the rise time for the second part of the field interval.
8. Enter **500.0 Oe** and **500.0 Oe** into the **H_x T-1(ps)** and **H_x T-2(ps)** edit boxes, respectively (no change). These are the fields at t = 100 and t = 2000 ps, respectively.
9. Click the **LOAD SECTION** button to log that section into the data structure.
10. Click **Accept Changes** to log your changes. Run the problem.

COMMENTS

Use the 2D Graphics utility (see page 31) to load Sample15.llg_conv file. On the y-axis, check **E(total)**, **E(exchange)**, **E(anisotropy)**, **E(demagnetization)** and **E(external)**. You will see the subtle interplay of the energies as the problem drives towards a solution. Also note that, as the field is increasing in time, the total energy is not constrained to decrease until such time as the field is turned off or maintained.

FEATURES

Structure:	150 nm x 150 nm x 10 nm
Sub-Element:	10 nm x 10 nm x 10 nm
Discretization:	15 x 15 x 1
Material:	Permalloy
Relaxation:	Time Dependence
Initialization:	Negative X in the X-Y plane
Hysteresis:	Time Dependent Field, 100 ps rise time to 500 Oe (fast!)

NOTE: In the graphic below, the interplay between the energy components and the energy pump into the system of the applied field is visible)

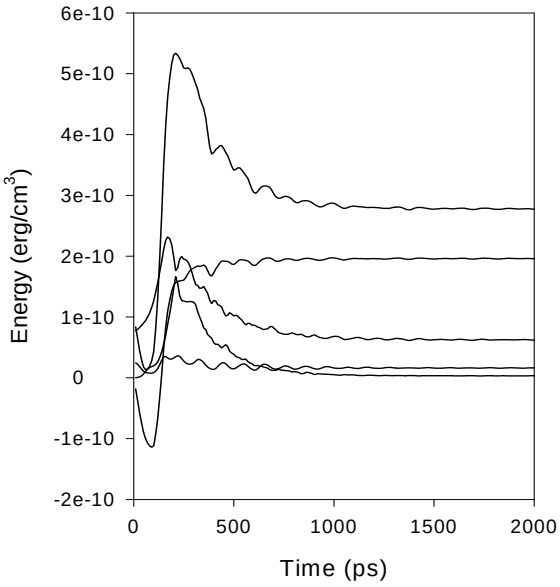
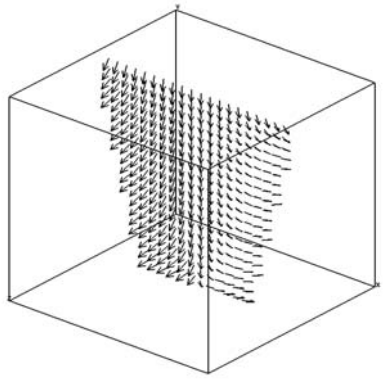


FIGURE 143. Time Dependence of Energies in Fast Rise Time Switching Field

CHAPTER 41

Sample Problem 16-Solid Pyramidal MFM Tip



This sample problem illustrates the simulation of a solid MFM tip's magnetization.

INPUT SHEET - MAIN PAGE

1. Initiate an LLG computation.
2. Enter the dimensions of the problem: X(nm) is 200 nm, Y(nm) is 200 nm and Z(nm) is 200 nm.
3. Enter the discretization for the problem: N_x is 20, N_y is 20 and N_z is 20.

INPUT SHEET - COMPUTATION PAGE

1. Click the **Computation** tab.
2. Check **Time (Faster)** and enter **2.0 ns** for the **(ps) Time Step**.
3. Select the **3D Complex FFT** method.
4. Click **Accept Changes** to log your changes.

INPUT SHEET - GLOBALS PAGE AND MATERIALS PAGE

1. Click the **Globals** tab.
2. Click the **Material Selector** button.
3. Select **Co** from the **Materials Page**. Click **Accept**. The Co properties should be entered in the edit fields of the Globals Page.
4. Choose **Z** as the easy axis.
5. Click **Accept Changes** to log your changes.

INPUT SHEET - INITIALIZE PAGE

1. Click the **Initialize** tab.
2. Initialize the magnetization along **Negative Z**.
3. Click **Accept Changes** to log your changes.

INPUT SHEET - BOUNDARY CONDITIONS PAGE

1. Click the **Boundary** tab.
2. Set the magnetization along $\mathbf{M_z}$ to **-1** for the **Top Z = $\mathbf{N_z}$**.
3. Click **Accept Changes** to log your changes.

MASK EDITOR

1. Check the **Commit Size** box on the **Main Page**.
2. Click the **Mask** button.
3. Either load the mask provided or make a pyramidal shaped mask.

COMMENTS

Even the strong anisotropy of Co is not enough to saturate the magnetization of the tip.

FEATURES

Structure:	200 nm x 200 nm x 200 nm
Sub-Element:	10 nm x 10 nm x 10 nm
Discretization:	20 x 20 x 20
Material:	Co
Initialization:	Negative Z

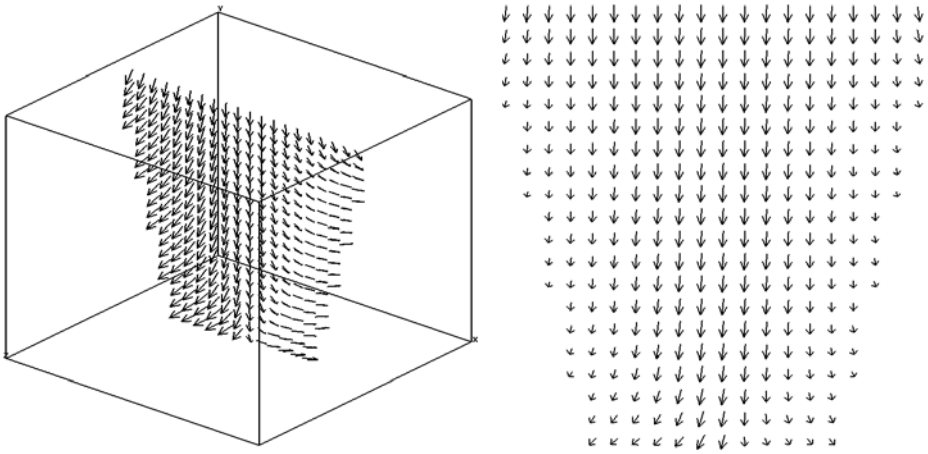


FIGURE 144. Midplane Magnetization of the Tip

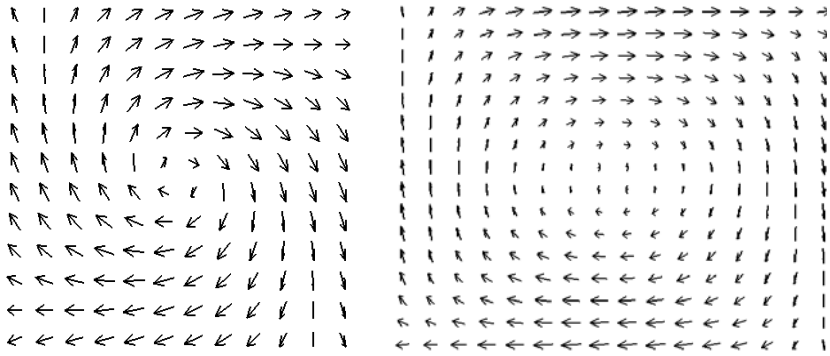
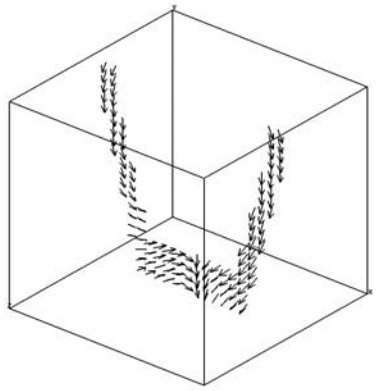


FIGURE 145. End and Mid-shank Magnetization of the Tip

CHAPTER 42

Sample Problem 17-Hollow Pyramidal MFM Tip



This sample problem illustrates the simulation of a hollow MFM tip's magnetization.

INPUT SHEET-MAIN PAGE

1. Initiate an LLG computation.
2. Enter the dimensions of the problem: X(nm) is 200 nm, Y(nm) is 200 nm and Z(nm) is 200 nm.
3. Enter the discretization for the problem: N_x is 20, N_y is 20 and N_z is 20.

INPUT SHEET-GLOBALS PAGE AND MATERIALS PAGE

1. Click the **Globals** tab, then click the **Material Selector** button.
2. Select **Co** from the **Materials Page**.
3. Click **Accept**. The Co properties should be entered in the edit fields of the Globals Page.
4. Choose **Z** as the **Easy Axis**.
5. Click **Accept Changes** to log your changes.

INPUT SHEET-BOUNDARY CONDITIONS PAGE

1. Click the **Boundary** tab.
2. Set the magnetization along $\mathbf{M_z}$ to **-1** for the **Top Z = $\mathbf{N_z}$**.
3. Click **Accept Changes** to log your changes.

INPUT SHEET-COMPUTATION PAGE

1. Click the **Computation** tab.
2. Check **Time (Faster)**.
3. Enter **2.0 ns** for the **(ps) Time Step**.
4. Select the **3D Complex FFT** method.
5. Click **Accept Changes** to log your changes.

INPUT SHEET-INITIALIZE PAGE

1. Click the **Initialize** tab.
2. Initialize the magnetization along negative Z.
3. Click **Accept Changes** to log your changes.

Mask Editor

1. Check the **Commit Size** box on the **Main Page**.
2. Click the **Mask** button.
3. Either load the mask provided or make a hollow pyramidal shaped mask.

COMMENTS

Even the strong anisotropy of Co is not enough to saturate the magnetization of the tip.

FEATURES

Structure:	200 nm x 200 nm x 200 nm
Sub-Element:	10 nm x 10 nm x 10 nm
Discretization:	20 x 20 x 20
Material:	Co
Initialization:	Negative Z

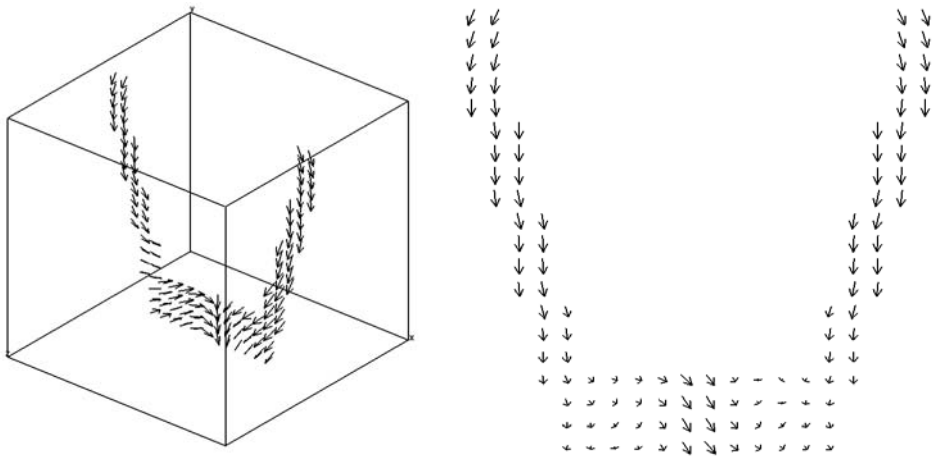


FIGURE 146. Midplane Magnetization of the Tip

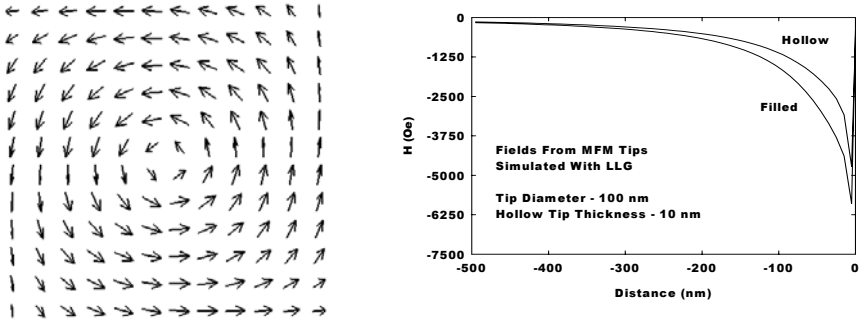
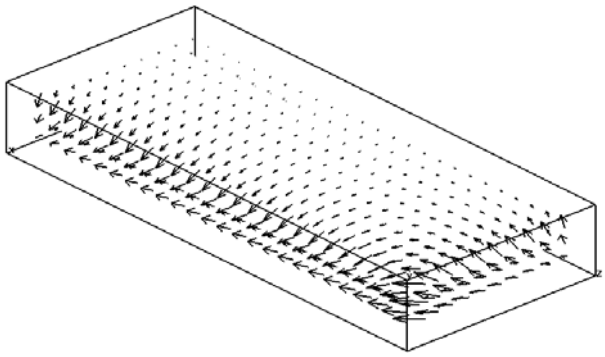


FIGURE 147. End-shank Magnetization and Field Dependence as a Function of Position Away from the Tip

CHAPTER 43

Sample Problem 18-Sample MFM Tip Interaction



This sample problem illustrates the interaction of a solid MFM tip with a sample.

INPUT SHEET - MAIN PAGE

1. Initiate an LLG computation.
2. Enter the dimensions of the problem: X(nm) is 500 nm, Y(nm) is 500 nm and Z(nm) is 100 nm.
3. Enter the discretization for the problem: N_x is 50, N_y is 50 and N_z is 10.

INPUT SHEET - COMPUTATION PAGE

1. Click the **Computation** tab.
2. Check **Time (Faster).**
3. Enter **2.0** for the **(ps) Time Step**.
4. Select the **3D Complex FFT** method.
5. Click **Accept Changes** to log your changes.

INPUT SHEET - GLOBALS PAGE AND MATERIALS PAGE

1. Click the **Globals** tab, then click the **Material Selector** button.
2. Select **Permalloy** from the **Materials Page**.
3. Click **Accept**; the Permalloy properties should be entered in the edit fields of the **Globals Page**.
4. Choose **X** as the **Easy Axis**.
5. Click **Accept Changes**.

INPUT SHEET - FIELDS PAGE

1. Click the **Fields** tab.
2. To make a poor approximation to the tip, pin with **H_z (Oe)** = **-10000** for layers 4-10. Click the **Load H-Pin** button after you enter each layer's field.
3. Click **Accept Changes** to log your changes.

INPUT SHEET - INITIALIZE PAGE

1. Click the **Initialize** tab.
2. Initialize using a **Vortex** in the **Z-Plane**.
3. Click **Accept Changes** to log your changes.

MASK EDITOR

Check the **Commit Size** box on the **Main Page**. Either load the mask provided or make a solid cylindrical tip 6 cells across and from layers 4-10. Layers 2 and 3 should be vacuum or masked out.

COMMENTS

The strong stray field from the magnetization of the tip is enough to grossly perturb the equilibrium magnetization of the sample.

FEATURES

Structure:	500 nm x 500 nm x 100 nm
Sub-Element:	10 nm x 10 nm x 10 nm
Discretization:	50 x 50 x 10
Material:	Permalloy
Initialization:	Vortex in Z

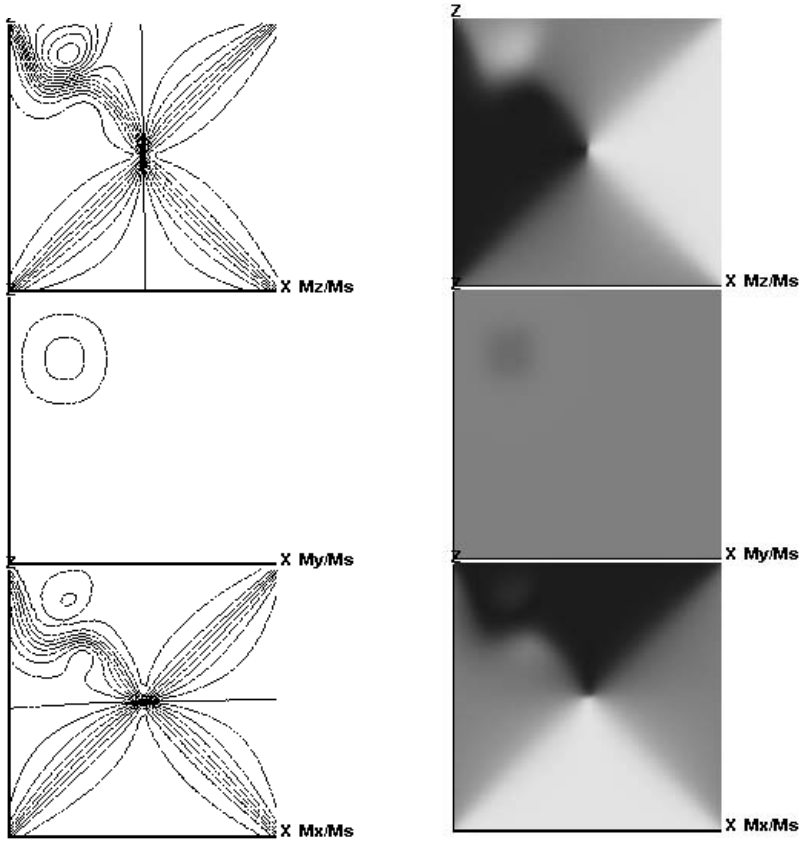
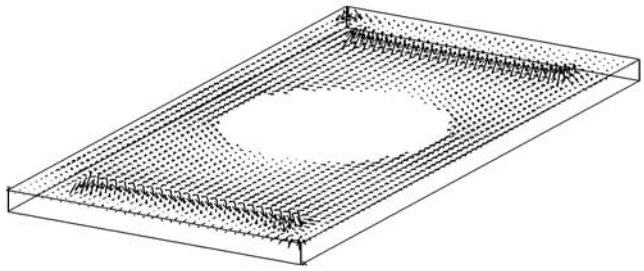


FIGURE 148. Magnetization Perturbed by the MFM Tip

CHAPTER 44

Sample Problem 19-3D Currents



In this sample problem 3D, current input is demonstrated. Although in this sample the 3D currents are generated and examined in and of themselves, it is clear how such currents can be incorporated into a larger and more complex problem.

INPUT SHEET - MAIN PAGE

1. Initiate an LLG computation.
2. Enter the dimensions of the problem: X(nm) is 640 nm, Y(nm) is 320 nm and Z(nm) is 30 nm.
3. Enter the discretization for the problem: N_x is 64, N_y is 32, N_z is 3.
4. Check the **Layers** box.

INPUT SHEET - LAYER PROPERTIES PAGE

1. Click the **Layer Props** tab.
2. Enter **30** into the **Layer (T)nm** box.
3. Click the **Material** button.
4. Select **Permalloy** from the **Materials Page** and click **Accept**.
5. Click the **LOAD LAYER PROP** button.
6. Click **Accept Changes**.
7. Check the **Pos Dep** box under **Structure Properties**.
8. Check the **Commit Size** box, which enables the Mask and PosDep buttons.
9. Click the **PosDep** button, which brings up the **PosDep Input Sheet**.

POSITION DEPENDENT SHEET - MAIN PAGE AND PARAMS PAGE

1. Left click on the graphics window to enable the drawing tool. Use the drawing tool to make a circle in the center of the structure, as in the figure above.
2. Select **All Layers**.
3. Click the **Params** tab.
4. Check the resistivity (**Rho**) box and enter **999999**.

5. Check the box next to the drop-down menu and select a color. Also, you ***MUST*** check the **CO** box in the **Graphics Control** for the color to appear in the graphics window. Click the **OGL Props** tab; then, click the **Modes** tab to access this feature.
6. Right click on the circle and select **Fill Region with Parameters**. This sets the resistivity in the hole. Save an *.llg_postion file and **Close PosDep Tool**.

INPUT SHEET - CURRENT PROPERTIES PAGE

1. Click the **Current** tab.
2. Set the **Time Independent Current** to **1000 μA**.
3. Check **3D** current and click the **Specify 3D Current** button. This brings up the **Current Mask Editor**.
4. On the third layer, use the rectangle tool to specify rectangular regions (as above) at either end of the Permalloy bar. Set the **Current** to **Enter** on one end and **Leave** on the other.
5. Click **Accept** and close the tool. You are ready to compute the current flow and field so start the simulation. The output is shown below.

FEATURES

Structure: 640 nm x 320 nm x 30 nm

Sub-Element: 10 nm x 10 nm x 10 nm

Discretization: 64 x 32 x 3

Material: Permalloy

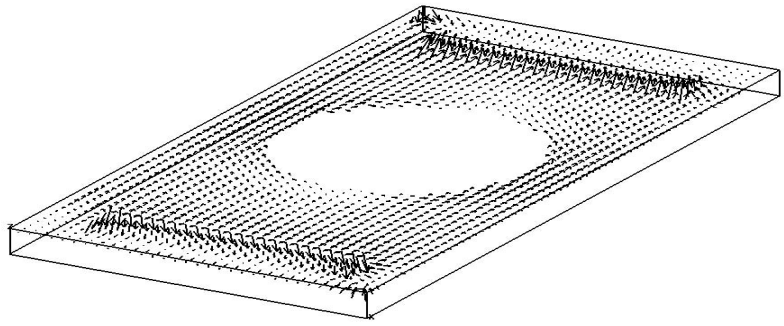


FIGURE 149. 3D Current Flow in a Bar with a Hole

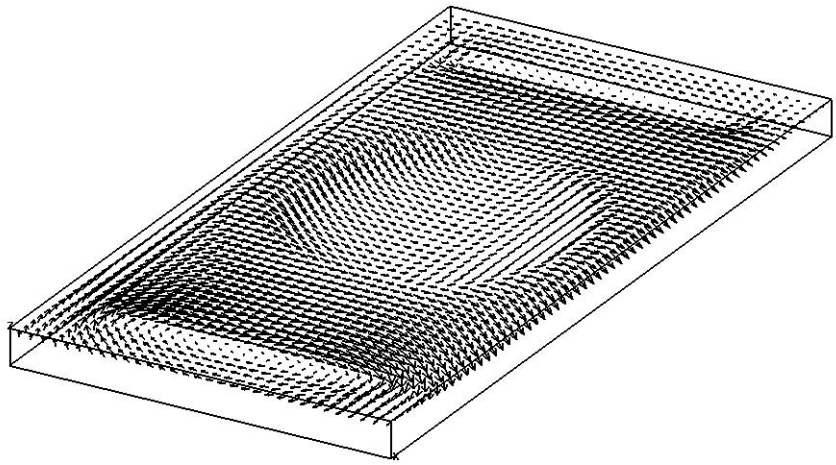
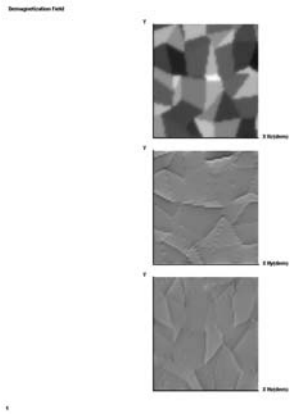


FIGURE 150. 3D Current Field in a Bar with a Hole

CHAPTER 45

Sample Problem 20-Media



This simple sample illustrates the use of the media option in the position dependent parameters page.

INPUT SHEET - MAIN PAGE

1. Enter the **Simulation Volume**: X(nm) is 640 nm, Y(nm) is 640 nm and Z(nm) is 10 nm.
2. Enter the discretization: N_x is 64 nm, N_y is 64 nm and N_z is 1 nm.

INPUT SHEET - GLOBALS PAGE AND MATERIALS PAGE

1. Click the **Globals** tab.
2. Set the magnetization to **350** and the anisotropy to **1000000**. These are reasonable parameters for media.

INPUT SHEET - LAYERS PAGE

1. Check the **Layers** box on the **Main Page**.
2. Click the **Layer Props** tab.
3. Set the parameters to the same values in the **Layers Page**.

POSITION - DEPENDENT PROPERTIES

1. Check the **PosDep** box under **Structure Properties** on the **Main Page**.
2. Check the **Commit Size** box to fix the discretization volume. This enables the Mask and PosDep buttons.
3. Click the **PosDep** button, which activates the position-dependent set of menus.
4. Click the **Params** tab. Check the anisotropy direction box and then click the **Any** button. Check the **X**, **Y** and **Z** boxes and the **Uniform** box for uniform deviates in all directions.
5. Click the **Exchange** tab and check the **Ax+**, **Ay+**, **Ax-** and **Ay-** boxes. These are the boundary edge exchange values. Leave them checked but set to 0.0, that is, with no exchange across the grain boundaries.
6. Click the **Media** tab and enter **100** nm for the **Mean Domain Dimension** and **40** nm for the **Deviation**.
7. Click **Tile the Surface**. Then, click the **Unify Grains** box to set the parameters uniformly within the grains.
8. Click the **Fill Parameters** button to fill the parameters into the tiled areas. Save your parameter file and start the calculation.

FEATURES

Structure: 640 nm x 640 nm x 10 nm

Sub-Element: 10 nm x 10 nm x 10 nm

Discretization: 64 x 64 x 1

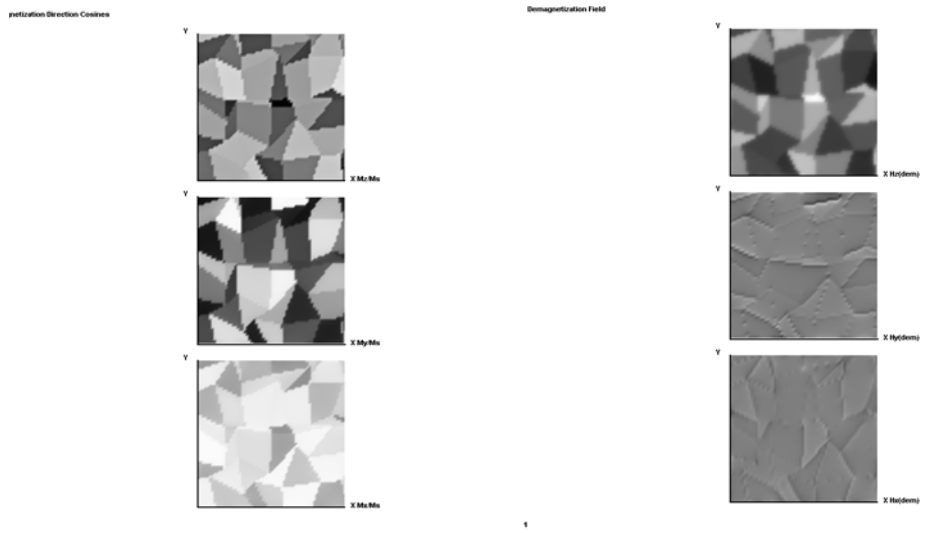


FIGURE 151. Media Magnetization Direction Cosines and Media Demagnetization Field

CHAPTER 46

Magneto Optical Simulations Supplement

INSTALLATION INSTRUCTIONS

The customized version of LLG Micromagnetics Simulator is named llg_v2_50_Custom_MO.exe and enclosed on the CD. The files on the CD will not install automatically and must be copied to your disk using Explorer. Please put the executable in the same directory as your other LLG files. The enclosed sample files can also be copied to your hard drive, but can be stored in any location.

THEORY OF OPERATION

Magneto-optical calculations have been implemented within LLG Micromagnetics Simulator. These simulations use the standard LLG computation engine while allowing the user to specify temperature dependent parameters which determine local temperature from reading a file or through computing a function. LLG has two models for computing the properties of magneto-optical materials. These models are termed 1-spin and 2-spin models. The distinction between the models is that the (effective) gyromagnetic frequency and (effective) damping constant are both functions of temperature in the 2-spin model but not in the 1-spin model.

1-SPIN MODEL

In the 1-spin model, the LLG equation

$$\frac{d\vec{M}(T,t)}{dt} = -\frac{\gamma}{1+\alpha^2}\vec{M}(T,t)\times\vec{H}_{eff}(T,t) - \frac{\gamma\alpha}{(1+\alpha^2)M_s(T,t)}\vec{M}(T,t)\times\vec{M}(T,t)\times\vec{H}_{eff}(T,t)$$

is solved for a position dependent system where the saturation magnetization $M_S(T,t)$, the anisotropy K(T,t), and the exchange stiffness A(T,t) are all functions of Temperature T and time t. The parametric dependence of the LLG input parameters on time is specified by either reading a file that contains T(x,y,z,t) data or through a function temperature input that computes T(x,y,z,t). The complication in solving the LLG equation for magneto-optical materials stems largely from the fact that mean-field theory is not a good approximation for systems near the transition temperature, i.e. near the Curie temperature, T_c. Here, the gyromagnetic frequency $\gamma = g\omega_e/2$ is usually determined from the free electron value of ω_e and the spectroscopic splitting factor, g = 2. The gyromagnetic frequency γ, the damping parameter α and the magnitude of the effective fields determine the time scales of interest. For time domain simulations, the nominal free electron gyromagnetic frequency is $\gamma = 1.78 \times 10^7$ (Oe sec-1). The damping parameter α is typically selected to

be between 0.005 and 2.0. The effective magnetic field on each magnetic moment is determined from the total system energy E_{tot} as

$$\vec{H}_{eff}(T,t) = \frac{-\partial E_{tot}(T,t)}{\partial\left(M_s(T,t)\vec{\alpha}\right)}$$

The effective magnetic field incorporates all the effects of exchange, anisotropy, external fields and demagnetizing fields. For the analysis of the equilibrium micromagnetic structure, the differential equation need not be integrated directly. Instead, notice that, for an equilibrium magnetization distribution, dM/dt = 0, which implies that the effective field, $\mathbf{H}_{eff}$, must be parallel to the magnetization **M**. The magnetization configuration can be relaxed iteratively by positioning each magnetization vector (almost) along the effective field vector direction throughout the mesh.

2-SPIN MODEL

In the 2-spin model, it is assumed that a strongly antiferromagnetically coupled 2-spin sub-lattice exists, such as in the TbFe or TbFeCo system. Here, following Mansuripur and Giles, the LLG equation can be adapted where now an effective gyromagnetic frequency, damping constant and effective field can be attributed to the lattice as a whole. The system of equations is now given by:

$$\frac{d\vec{M}(T,t)}{dt} = -\frac{\gamma_{eff}}{1+\alpha_{eff}^{\ 2}}\vec{M}(T,t)\times\vec{H}_{eff}(T,t) - \frac{\gamma_{eff}\,\alpha_{eff}}{(1+\alpha_{eff}^{\ 2})M_s(T,t)}\vec{M}(T,t)\times\vec{M}(T,t)\times\vec{H}_{eff}(T,t)$$

$$\gamma_{eff}(T,t) = \frac{M_1(T,t)-M_2(T,t)}{M_1(T,t)/\gamma_1 - M_2(T,t)/\gamma_2}$$

$$\alpha_{eff}(T,t) = \frac{\alpha_1 M_1(T,t)/\gamma_1 + \alpha_2 M_2(T,t)/\gamma_2}{M_1(T,t)/\gamma_1 - M_2(T,t)/\gamma_2}$$

$$\vec{H}_{eff}(T,t) = \frac{M_1(T,t)H_{eff,1} - M_2(T,t)H_{eff,2}}{M_1(T,t)-M_2(T,t)}$$

where $H_{eff,1}$ and $H_{eff,2}$ are the effective fields on sublattices 1 and 2 respectively, and the new H_{eff} is effectively the effective field computed through normal means with M set to M_1-M_2. As Mansuripur points out, there is a singularity in the gyromagnetic frequency and damping constant at the angular momentum compensation point, but that singularity does not appear in the LLG equations due to the $1/(1+\alpha^2)$ scaling.

The main problem is in determining what state the spin system should take once that part of the spin system is above the Curie temperature, and, what happens when those spins above the Curie temperature are cooled below the T_c. This implementation makes the following assumptions:

- When a spin at $T < T_c$ transitions to $T > T_c$, save the spin state in memory and set the direction cosine to zero (i.e. no energy is contributed to the magnetic system and spins outside of the Curie rim cannot couple via exchange to those within the Curie rim.
- When a spin at $T > T_c$ transitions to $T < T_c$, compute the effective field at that point and set the spin state to the effective field direction if $H_{eff} > H_c$, or set the direction to the stored spin direction if $H_{eff} < H_c$. This makes the assumption that the dynamics for the spin response are fast as the spin makes the transition from being above the Curie

temperature to being below it. This is consistent with Mansuripur's assumption that, at the compensation temperature and since the damping constant is diverging, the spin should be instantly aligned with the effective field. Further, since the in-field critical behavior has ordering about T_c, so long as $H>H_c$, it seems sensible to order along the field direction.

- When $T = T_{compensation}$, set the direction cosine along the effective field direction instantly.

For all other situations, the equation is solved directly. Also note that when the gyromagnetic frequencies are identical for the two spin systems that the system gyromagnetic frequency is fixed and constant.

INITIATING A MAGNETO-OPTICAL CALCULATION IN LLG

All magneto-optical calculations in LLG must be done using position dependent parameters. Please see the LLG Micromagnetics Simulator User Manual for a complete description of initializing computations for position dependent parameters. Once a problem has been initialized, you may click on the MO page to activate the main input page for specifying magneto-optical parameters, shown below.

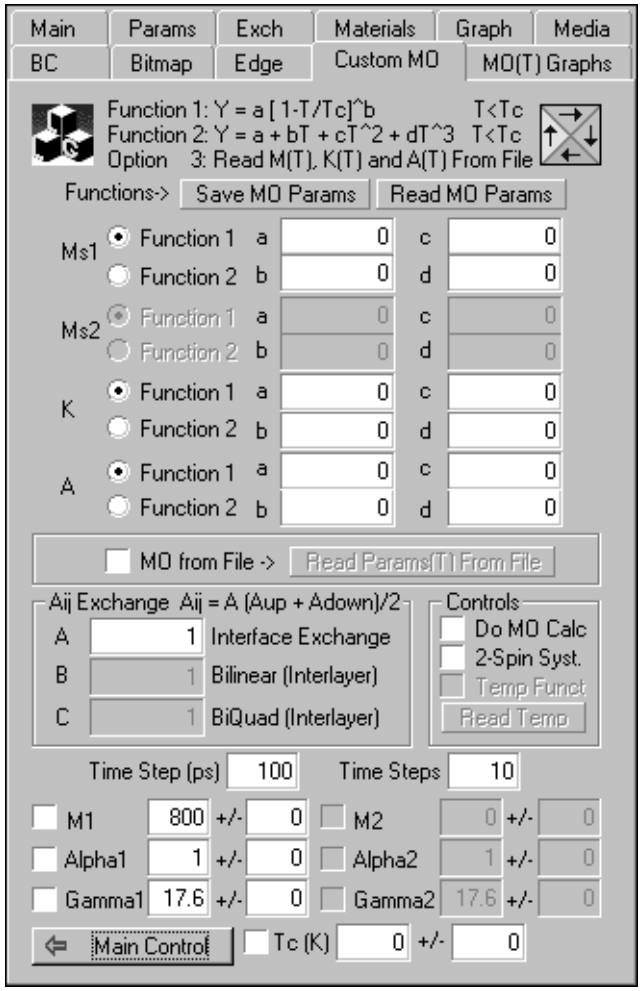


FIGURE 152. Position Dependent Sheet - MO Main Page

When you run a magneto optical problem using LLG, extra memory is allocated for $M_1(x,y,z)$, $M_2(x,y,z)$, $\alpha_1(x,y,z)$, $\alpha_2(x,y,z)$, $\alpha(x,y,z)$, $\gamma_1(x,y,z)$, $\gamma_2(x,y,z)$, $\gamma(x,y,z)$, $T_c(x,y,z)$, and $T(x,y,z)$. In addition, memory is allocated for the input temperature array read from file, should you select that option.

SPECIFY AN MO CALCULATION

To signal LLG that you will be performing an MO computation, check the **Do MO Calc** box. If you wish to perform a 2-spin computation, check the **2-Spin Syst** box. You must enter the **Time Step (ps)** for each segment of the file that is to be read, and the total number of **Time Steps**. Your input file must have at ***MOST*** N time steps. Your time evolution as specified (when read from a file) will be $N_{steps}T_{per\text{-}step}$.

SPECIFYING POSITION DEPENDENT PARAMETERS

You may specify the position dependent parameters for each input variable by (1) checking the box to signal LLG that your parameter is to be changed, (2) entering the nominal value in the edit box, (3) entering the gaussian random component of the value adjacent to the +/- edit box, (4) drawing the appropriate shape using the position dependent editing tools, (5) specifying either a single layer, all layers or a range of layers from the LLG Main Position Dependent Parameters Page, and (6) by right clicking on the defined shape and selecting fill region. You may repeat this process as many times as you choose to. Remember to save your position parameters. **IMPORTANT NOTE:** Your custom version of LLG Micromagnetics Simulator saves position dependent files in a different format than the regular version of LLG. The custom version saves, in addition to the normal position dependent parameters, the position dependent magnetization of both spin systems, the gyromagnetic frequencies and damping parameters, as well as the local Curie temperature. LLG uses the same file suffix to specify these files. If you attempt to read a position dependent file saved with the normal version of LLG with the customized version, the file read will fail since the added arrays are not written to the file. Please keep your files written with the customized LLG in a separate directory from those written with the normal version of LLG. Remember, load your files before you begin to specify your problem and be sure to save your position dependent data prior to beginning a simulation.

SPECIFYING PARAMETERS AS A FUNCTION OF TEMPERATURE

You have two options for specifying MO properties as a function of temperature: either using defined functions or reading data from a file.

SPECIFYING PARAMETERS AS A FUNCTION OF TEMPERATURE USING FUNCTIONS

LLG supports two different function inputs to generate temperature dependent data. These functions scale as the normalized temperature $T_n=(T/T_c)$.

$$F = a(1 - T/Tc)^b \qquad T < T_c$$

$$F = a + b(T/Tc) + c(T/Tc)^2 + d(T/Tc)^3 \qquad T < T_c$$

When $T > T_c$, F = 0.0. It is extremely important to note that this scaling will apply to all parameters in the array. If you wish some parameters to remain temperature independent, then simply set the Curie temperature of that site to a very high value (10x higher than the maximum temperature reached in the problem). These function inputs allow you to set the magnetization as a function of temperature variably throughout the grid. **IMPORTANT NOTE 1:** For example, the magnetization in a 1-spin problem will be constructed from $M_1(T,t,x,y,z)= M_1(x,y,z)F_{M1}(T)$, and in a 2-spin problem, $M(T,t,x,y,z)= M_1(x,y,z)F_{M1}(T)-M_2(x,y,z)F_{M2}(T)$. **IMPORTANT NOTE 2:** The radius of convergence for a problem is fixed primarily by the exchange field which scales as A/M. If you want your problem to remain stable at all temperatures, you must be sure that A->0 faster than M->0 at T_n->1.0.**IMPORTANT NOTE 3:** When specifying properties using functions, all properties must be specified using functions (i.e. you cannot mix functions and data options).

SPECIFYING PARAMETERS AS A FUNCTION OF TEMPERATURE USING DATA READ FROM FILES

The second input option for parameters that LLG supports reads parameter data from a file. The format is in comma separated values so that you can prepare your data using Microsoft Excel and save the file using the Comma Separated Value (*.csv) option. The data are saved in columns in the following format: (headings are not part of the file itself)

T/T_c	M/M(T=0)	A/A(T=0)	K/K(T=0)	M_1/M(T=0)	M_2/M(T=0)
0.0,	1.0,	1.0,	1.0,	1.0,	1.0
0.1,	0.9,	0.9,	0.9,	0.95,	0.85
0.2,	0.8,	0.8,	0.8,	0.90,	0.70,
.	.	.	.	.	.
.	.	.	.	.	.

Once data are read from a file, they are linearly interpolated onto a grid of equally spaced base points separated by $T/T_c = 0.002$ (i.e. 501 total points). You should remain mindful of this scheme when entering data as interpolation of K and M_S near T_c can radically alter nucleation properties.

SPECIFYING TEMPERATURE DATA: READ FROM FILE OR MOVE A GAUSSIAN PROBE

You may read temperature data from a file or use LLG's internal temperature profiler. If you want to use LLG's internal temperature profiler, then check the **Temp Funct** box on the main MO Page. If you want to read data from a file, then ***DO NOT*** check the **Temp Funct** box on the main MO Page.

When you have checked the **Temp Funct** box on the main MO Page and you click the **Read Temp** button, you will be prompted by the **Functional Temperature Probe** dialog box as shown below. The generated function has the following form:

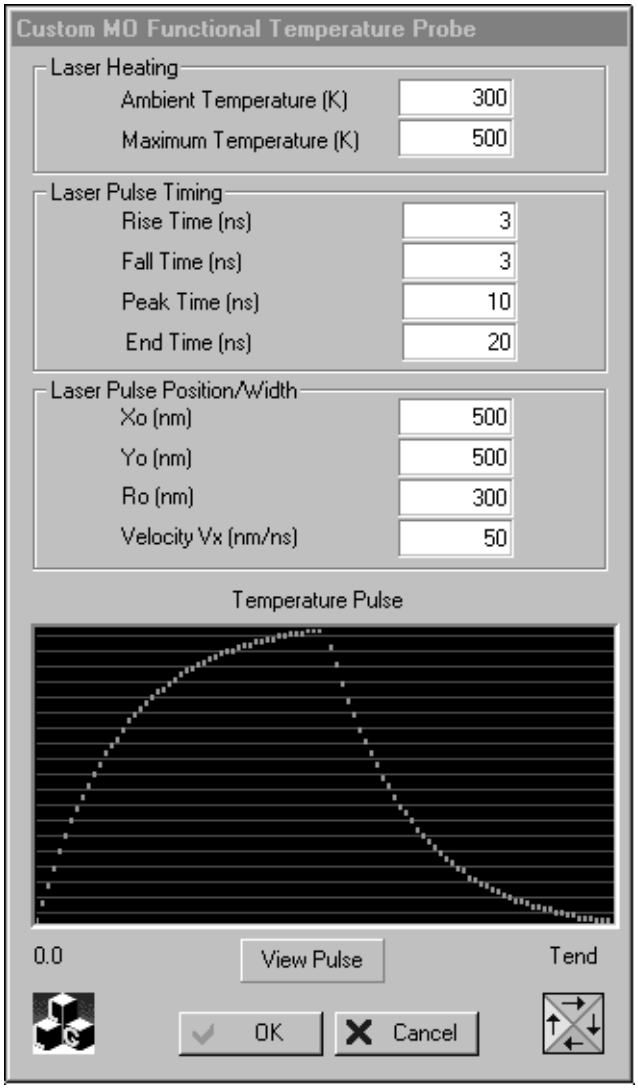


FIGURE 153. Position Dependent Sheet - MO Functional Temperature Probe Page

$$T(x, y, z, t) = T_{amb} + (T_{max} - T_{amb}) f(t) e^{-[(x - x_o - v_{xo} t)^2 + (y - y_o)^2]/R_o^2}$$

where

$$f(t) = \frac{[1 - e^{-t/\tau_1}]}{[1 - e^{-\tau_{peak}/\tau_1}]}$$

for $t < \tau_{peak}$ and

$$f(t) = 1 - \frac{[1 - e^{-(\tau_{peak} - t)/\tau_2}]}{[1 - e^{-(\tau_{peak} - \tau_{end})/\tau_2}]}$$

for $\tau_{peak} < t < \tau_{end}$. The input variables are obtained from the dialog as: Ambient Temperature (K) [T_{amb}]; Maximum Temperature (K) [T_{max}]; Rise Time (ns) [τ_1]; Fall Time (ns) [τ_2]; Peak Time (ns) [τ_{peak}]; End Time (ns) [τ_{end}]; Xo (nm) [x_o]; Yo (nm) [y_o]; Ro (nm) [R_o] and Velocity (nm/ns) [v_{xo}]. In order to view the temperature pulse profile in time click the **View Pulse** button.

READ FILE CONTAINING TEMPERATURE DATA

When you click the Read Temp button, you will prompted to enter a file name. Then you will be offered the following dialog with options for processing your temperature data. Remember, since you are reading files not specifically designed for LLG, you are responsible for ensuring that the file is properly formatted and that the data that you specify about this file in the dialog below is correct.

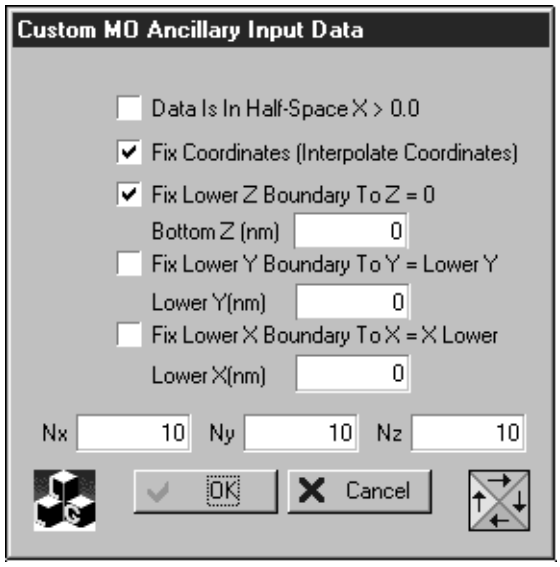


FIGURE 154. Position Dependent Sheet - Ancillary Input Data Page

This version of LLG has been programmed specifically to read input files formatted to your specifications. You must correctly enter the number of finite element output nodes in X (**Nx**), the number of finite element output nodes in Y (**Ny**),

and the number of effective finite element nodes in Z (**Nz**). The effective number of finite element nodes in Z is that number written in the file regardless of the actual numbering scheme used. In the sample file sent, the effective number in Z is 4 (see LLG_full.txt on the accompanying CD). The rest of the inputs are optional. Check the **Data Is In Half-Space Y>0.0** box if the finite element data is from the half-space in Y. LLG will take the half of the data rendered to the file and reflect it about the Y = 0.0 plane. Check the **Fix Coordinates (Interpolate Coordinates)** box if you would like LLG to use the coordinates in your data and the coordinates in LLG as real coordinates. If you do not check this box, LLG will match up the edges of the two systems and interpolate the temperature data on the LLG grid, assuming that your data are fixed to the LLG grid. If your data are keyed to real coordinates, then do ***NOT*** select this option. You may shift your data by fixing the lower boundary. This will shift your data as follows:

Check the **Fix Lower Z Boundary to Z = 0** and enter the shift value in the **Bottom Z(nm)** edit box. If you enter the coordinate of the lower Z surface of the active data area (135nm in LLG_full.txt on the accompanying CD), your data's lower surface (135nm) will be shifted to 0.0 nm internal to LLG i.e. $Z_{LLG} = Z_{FEM}$ - Z(**Bottom Z(nm)**)**.**

Check the **Fix Lower Y Boundary to Y = Ylower** and enter the shift value in the **Lower Y(nm)** edit box. If you enter the coordinate of the lower Y surface of the active data area internal to LLG i.e. $Y_{LLG} = Y_{FEM}$ - Y(**Lower Y(nm)**)**.**

Check the **Fix Lower X Boundary to X = Xlower** and enter the shift value in the **Lower X(nm)** edit box. If you enter the coordinate of the lower X surface of the active data area (135nm in LLG_full.txt on the accompanying CD), your data's lower surface (135nm) will be shifted to 0.0 nm internal to LLG i.e. $X_{LLG} = X_{FEM}$ - X(**Lower X(nm)**)**.**

Loading and Saving MO Parameter Files

You may load and save MO parameter files by clicking the buttons at the top of the main LLG MO parameter page. These files contain all the functional parameter data, temperature probe data and file reading/shifting data specific to your problem. Once you have saved your parameters to a file, you can reload them and edit them using the tools provided in LLG or using a standard file editor. Remember, your comma separated values are NOT SAVED to this file. Additionally, no LLG file tag is associated with this file type. In the data provided, these files have *.MO_Parameters as a suffix.

Viewing MO data using MO Graphics

You may visualize your MO data using the MO(T) Graphs Page. In the edit fields at left, enter the nominal values for M_1, M_2, M, A, K. If you are computing a 2-spin system, LLG will form M from M_1 and M_2. Since LLG uses the functions and input data only for scaling (i.e. position dependent M_1, M_2, M, A and K are each scaled by these functions with their own position dependent T_c). Just click on the appropriate parameter and it will be displayed in the graphics window at the top of the page (as shown in the figure below). Once you have either entered a file name for the temperature data, or you have defined an appropriate function, you can click the **Preview Temperature File** button to see a movie of your temperature data as specified and projected onto the LLG grid.

Comments

Nucleation local to the rim of the Curie disk depends quite sensitively on the parameters specified there. The code will nucleate a site if the effective field is greater than the coercive field at the temperature specified.This means that the shape of the Hc(T) curve near Tc can greatly change the characteristics of the problem. In addition, the value of Ms at T near Tc can greatly change the properties of the nucleation, in that a steeper rise in Ms near the Curie temperature can lead to inversely magnetized sub-domain formation in the demagnetization field of cells local to the Curie rim. Be sure to experiment with your parameter selection prior to initiating a problem in LLG by examining the size and shape of Ms and Hc near Tc.

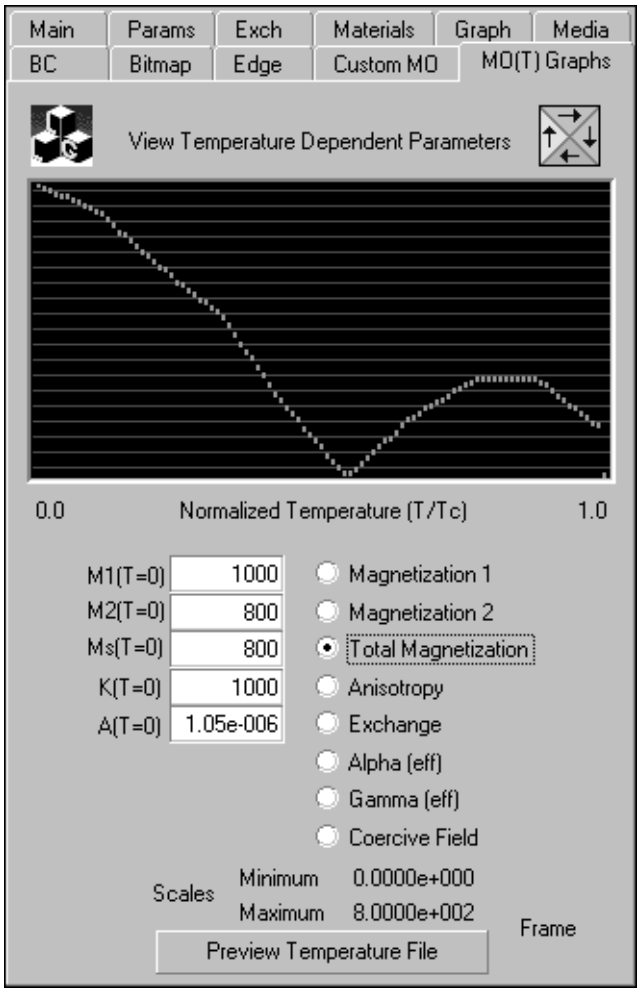


FIGURE 155. Position Dependent Sheet - MO(T) Graphs Page

SAMPLE PROBLEM

Some sample problems are provided to illustrate LLG's basic functionality for performing MO calculations. These problems are based on content from Mansuripur's book on MagnetoOptical Recording. The essential problem is to examine nucleation in the region around a gaussian beam that heats the specimen above T_c and then cools. The sample is 512 x 512 x 50 nm, 128x128 pixels. The nominal properties for the materials are:

Property	Value	Units	$A(F_1)$	$B(F_1)$
Ms	180	emu/cm^3	1.0	
Ku	2000000	erg/cm^3	1.0	
A	0.4	μerg/cm	1.0	
T_c	441	K	N/A	N/A
τ_1	0.1	ns	N/A	N/A
τ_2	0.1	ns	N/A	N/A
τ_{peak}	0.1	ns	N/A	N/A
τ_{end}	0.1	ns	N/A	N/A
T_{amb}	300	K	N/A	N/A
T_{max}	500	K	N/A	N/A

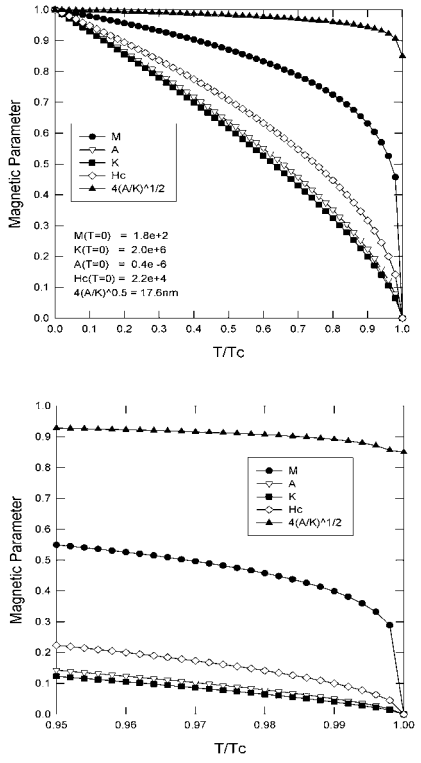


FIGURE 156. Magnetic Parameters for the Sample Problem.

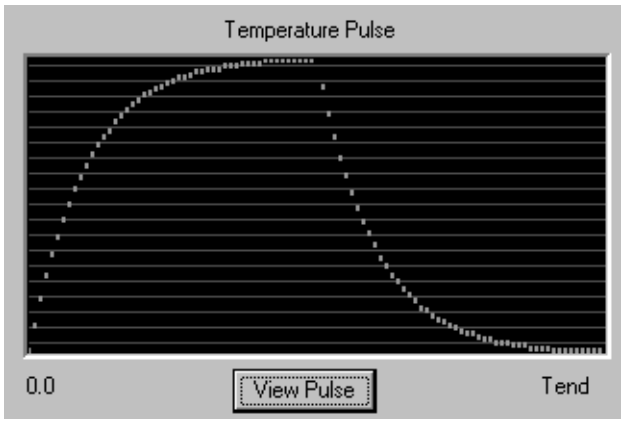


FIGURE 157. Temperature Profile for the Sample Problem

This sample was run through heating/cooling cycles in a variety of external fields.

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